MANUALS OF ELEMENTARY SCIENCE

ELECTRICITY.

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BY THE LATE

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PREFACE.

THE facts described under the heading Electricity and Magnetism form a group of phenomena neither rare nor isolated, but continually and universally present. These facts are connected not only with each other, but with all physical facts, by definite laws.

The following little treatise may, the Author hopes, enable a student partly to understand the nature of these laws and to perceive some of the grounds on which they rest, even though he may not have sufficient mathematical knowledge for their application to special problems.

The object of the book will be attained if it induces beginners to regard the facts of Electricity and Magnetism not only as interesting or curious in themselves, but as the groundwork of a science, or rather as part of the groundwork of the general Science of Physics.

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ELEMENTARY ELECTRICITY.

CHAPTER I.

FUNDAMENTAL CONCEPTIONS OF ELECTROSTATICS.

§ 1. *Electricity. Electric Fluids.*—Electrical phenomena are described in language which implies the existence of two imponderable fluids called positive and negative electricity. Thus a body exhibiting certain electrical properties is said to contain a *charge* of positive or of negative electricity; we also speak of the *quantity* of electricity with which the body is charged. All bodies are conceived as containing an indefinite amount of a neutral fluid which is not itself electricity, but from which equal quantities of electricity of opposite signs are obtained by decomposition whenever electricity is brought into evidence. When electricity disappears it is conceived that equal quantities of the positive and negative fluid have combined to form the neutral fluid. On any hypothesis the two electricities, inasmuch as they always come into evidence and disappear simultaneously, must be considered as two parts of one phenomenon. It is improbable that either the neutral fluid or the electric fluids have any substantial existence, but the terms used in describing material fluids enable us to describe accurately the electrical properties of matter.

§ 2. *Conductors and Insulators.*—Certain materials allow electricity to pass readily throughout their substance, and these are called *conductors*. Materials which do not allow electricity to pass through them are called *insulators*. Many materials neither insulate nor

conduct well. The metals, charcoal, common water, solutions and moist bodies, such as earth or the human frame, are conductors. Air, whether damp or dry, and all gases, including dry steam, most kinds of glass, sulphur, india-rubber, vulcanite, gutta-percha, shellac and other resins, some oils, dry silk and cotton, are insulators. Wood, stone, and flax are neither good conductors nor good insulators. The difference between conductors and insulators is a difference of degree; all solids and all liquids resist the passage of electricity to some extent, and none prevent that passage entirely.

§ 3. *Modes of Producing an Electric Charge.*—It is probable that any two different materials in contact are in a different electrical condition; but the difference is usually so slight as to require delicate apparatus for its detection. When, however, two *insulators* are pressed together, and much more when they are rubbed together, the one becomes sensibly charged with positive and the other with negative electricity. The words "electrified" and "electrically excited" are also used to describe their condition. Each substance in the following list usually becomes positively electrified when rubbed or pressed against any of the substances placed after it; but negatively electrified when rubbed or pressed against any of the substances preceding it in the list. We obtain the most marked effects by using pairs of substances which are far apart in the list:—

Cat's fur, glass, ivory, silk, the hand, wood, sulphur, flannel, cotton, shellac, caoutchouc, resin, gutta-percha, metals, gun-cotton.

Differences which are apparently trifling, such as the dye of a stuff or the degree of polish on a body, cause a marked difference in the position of the material in such a list as the above. It not unfrequently happens that a body which we expect from previous experience to find charged with positive electricity is found to be really charged negatively.

Friction is generally named as the cause of the

electricity called into evidence when bodies are rubbed together, but the quantity of electricity produced bears no relation to the amount of friction as measured by the *work* done. Friction, therefore, is not the *cause* of electricity in the same sense as it is the cause of heat. Possibly simple *contact* between dissimilar substances is the essential condition which necessarily involves the production of electricity. The increased effect due to rubbing may perhaps be simply due to the close contact between numerous particles of the two bodies which accompanies the action of rubbing. The friction also cleans, warms, and dries the surfaces, and clean, warm, dry surfaces favour insulation, and so prevent the escape of the electricity which is called forth. Practically, to obtain marked electrical effects from the contact of two insulators these must be rubbed together.

Two *conductors* in contact, whether solid or liquid, charge one another with electricity of opposite signs. Thus if two metals touch, as zinc and copper, the one, as zinc, acquires a positive charge; the other, as copper, acquires a negative charge. Friction between the metals neither increases nor diminishes this charge, which, inasmuch as metals are conductors, is instantly distributed over the metals. When insulators such as glass or resin are pressed or rubbed together only those parts are at first electrified which come into actual contact. The electricity in time spreads further, because the insulation is imperfect.

The difference in the electrical condition of two conductors in contact is much less than that of two insulators which have been rubbed together. This distinction between conductors and insulators is one of degree and not of kind, for both among conductors and insulators some pairs produce by their contact a much greater difference of electric condition than others. Contact or friction between a conductor and an insulator produces a distributed charge on the conductor and a charge on the insulator which is at first

confined to the places of contact. Two insulators which have been rubbed together retain their charges unmodified for some time after their separation. This is not the case with conductors.

An electric charge is not a rare or isolated phenomenon requiring artificial precautions for its production. Every body round us is in a different electrical condition from all other bodies with which it is in contact. The air itself by its contact affects the electrical condition of all bodies. The charges produced by these universal contacts are, however, so small that they require the finest apparatus for their detection; they may therefore be neglected while we study the more marked or evident electrical phenomena.

§ 4. *Force between Electric Charges. Quantity.*—The presence of electricity is recognised by the observation of *force* due to the charge. Bodies charged with electricities of the same kind repel one another in virtue of the charge; bodies charged with electricities of opposite kinds attract one another. The fluid with which any conductor is charged cannot leave that body, being retained by the surrounding insulator; any force acting on the electric fluid acts therefore on the body to which it is confined. Adopting this language, we shall henceforth say that attraction exists between electric charges of opposite sign, and repulsion between electric charges of the same sign.

Equal charges will under equal conditions produce equal forces. We have thus the means of ascertaining whether two equal bodies, as, say, spheres of equal diameter, are equally charged with electricity; to do this we have only to observe whether at equal distances they exert equal forces on a third body charged with electricity. Means exist by which equal charges can be added so to accumulate on one conductor, and we find experimentally that two equal quantities of the same sign when thus added attract or repel a given charge on another body with twice the force which was exerted by each singly when in the same place, also

that two equal quantities of opposite sign when added neutralise one another so as after their combination to exert no force. These facts enable us, independently of all hypothesis as to the nature of electricity, to treat an electric charge as a measurable *quantity*. The measurement is made by measuring forces. Instruments for numerically measuring or comparing the forces due to various charges of electricity are called *electrometers*. Instruments which simply indicate the existence of a force due to a charge are called *electroscopes*. The *unit* quantity of electricity is that which repels another equal quantity at unit distance with unit force.

§ 5. *Distribution of Electricity on Conductors.*—The distribution of electricity at rest on a conductor is experimentally found to be that given by calculations based on the law that *the force between each indefinitely small quantity or particle of electricity and every other equal quantity varies inversely as the square of the distance between them. This force is one of attraction between electricities of different signs, and one of repulsion between electricities of the same sign.* This law can be proved to be rigidly true by experiments on distribution, and can by experiment be shown to be approximately true for charges on small spheres. One consequence of the above law is that any electricity imparted to a conductor must when at rest lie wholly on the surface, although we shall see hereafter that electricity moving from place to place passes through and pervades the whole substance of the conductor. Another consequence of the law is that electricity accumulates in greater quantities at all sharp corners or sharp points of a conductor than on flat or gently rounded surfaces. A third consequence is that on any conductor forming a closed shell, inside which there is nothing but air or some other insulator, the electric charge will be wholly situated on the external surface. Let it be at once noted that the electricity described as being on the surface of the conductor might in all cases be equally well described as situated

on the surface of the insulator which bounds that conductor.

§ 6. *Potential.*—The quantity of electricity in an electric charge is a conception analogous to that of a quantity of material fluid, such as water, and so the idea represented by the *electric potential* of a point or of a charged conductor is analogous to that of the *level* of a point in space or of a body of water. The analogy is not with level as indicating geometrical position, but with level as indicating a condition in virtue of which gravitating matter, such as water, can do *work* in descending to a lower level. As water will under the influence of gravitation, if not restrained, descend from a point at a higher level to a point at a lower level, and do work while so descending, so positive electricity will under the influence of electric forces, if not restrained, move from a point at a higher potential to a point at a lower potential, and do work while so moving. The manner of the motion may be analogous either to the flow of water through a pipe, as when electricity flows through a conductor; or it may be analogous to the motion of a body of water transported in a closed vessel, as when an electrically charged body moves, carrying its charge of positive electricity from a point at a higher to a point at a lower potential. The path may be direct, as when the vessel of water falls vertically and the electrified body moves in the direction of the attracting force; or the path may be indirect, as when we constrain the vessel of water or charged body to follow a circuitous track; the work done will be the same whether the path be direct or circuitous. The motion of the electric charge, or its tendency to move along a given path, will continue so long as each point of the path is at a lower potential than that which preceded it. A negative charge tends to move from a place of lower to a place of higher potential.

Electrified bodies, inasmuch as they attract or repel electricity, produce that condition of space around and

within them in virtue of which each point of the space has an electric potential. As there are surfaces of equal level round the earth, so there are surfaces of equal potential round any electrified body or bodies. When a quantity of electricity so small as not itself to disturb the electric conditions produced by the other charge or charges is moved over these *equipotential* surfaces as they are called, the small quantity or charge experiences no force due to electricity, so that no work is done, or required by, or for, the action of moving the small quantity along these surfaces. We will henceforth call a small quantity of electricity on a small conductor, used to explore space by testing the force which other electrified bodies produce at each point, a *test charge.* When electricity is not in motion through a conductor each point of the space occupied by the conductor is at one and the same potential, which is termed *the* potential of the conductor; for if at any point the potential were higher or lower than at another, positive electricity would move from the higher to the lower point through the conductor. If no charge were originally present at either point the neutral fluid (§ 1) of the conductor would separate, and positive electricity would go to the point of low potential and negative electricity to the point of high potential until the potentials of the two points were equalised. It is obvious from what has been said above that positive electricity tends by its presence to raise the potential both of the place it occupies and of surrounding points, whereas negative electricity tends to lower it.

As we require arbitrarily to choose some level, such as Trinity high-water mark, above which heights are positive but below it negative, so we arbitrarily choose the potential of the earth, where experiments are being made, as zero. *Definition*:—THE ELECTRIC POTENTIAL OF A CONDUCTOR *is that condition of the conductor in virtue of which electricity tends to pass from the conductor to the earth, and in so passing to do work.*

THE POTENTIAL OF ANY POINT *in space is that condition*

of the point in virtue of which a test charge would tend to pass from that point to the earth and do work in so passing. It is to be noted that the test charge is here assumed so small as not itself to modify the potential of any point.

THE DIFFERENCE OF POTENTIALS *between any two conductors is that difference of condition in virtue of which electricity tends to pass from one to the other and do work in so passing.*

The difference of potential between two POINTS OF SPACE *is that difference of condition in virtue of which a test charge would tend to pass from one to the other and do work in so passing.*

It follows from these definitions that *the* potential of a conductor or point is merely the difference of its potential from that of the earth.

It also follows that if the difference of potentials between A and B be m, and the difference of potentials between B and C be n, the difference of potentials between A and C will be $m+n$.

Difference of potentials is *numerically expressed* or *measured* by the number which expresses or *measures* the *work* which a test charge would do in passing from one point or one conductor to the other, as the difference between two gravitation levels might be measured by measuring the work which a constant weight would perform in falling from one level to the other. The *unit* difference of potentials exists between two points when a unit quantity of positive electricity (§ 4) acting as a test charge, will do a unit of work when passing from the point of higher to the point of lower potential.

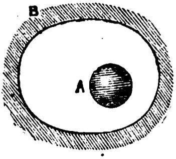

Fig. 1.

§ 7. *Induction.*—Let the space round an electrified body A (fig. 1) be called the *electric field* of this body; this field is necessarily filled with some insulator, such as air or india-rubber, to retain the charge. If the charge on A, which we may call a, be positive, the

potential of the body will be greater than that of any point of its surrounding field. The potential of points in this field gradually decreases as their distance from A increases. This potential will at all points be positive if the insulator is boundless. Now let an uninsulated conducting shell B be placed so as to bound the field, completely surrounding it and the enclosed body A. The potential of the uninsulated conductor B is zero, but the potential of each point of the surface of the insulator touching B will, when B is absent, be positive; consequently when the uninsulated shell is placed on the insulator negative electricity will flow from the uninsulated shell or the earth to this surface until equilibrium is attained, which can only be the case when the sum of the effects due to the charge on A and the new charge $-b$ on the inner surface of B is nil at all points outside the surface bounding the insulator. From the law in § 5 it can be proved that to produce this neutralisation of effects the quantity of negative electricity $-b$ on B must be equal to $-a$. The charge called into existence on B by the influence which electricity on A exerts across an insulator is called an *induced* charge. The action is called *Electrostatic induction*, or simply induction. The insulator across which the action takes place is called a *dielectric.*

A positive charge induces a negative charge across the dielectric; similarly a negative charge induces a positive charge across the dielectric. Returning to the case where the inducing body is surrounded by a complete shell, we observe that the induced charge results from a decomposition of the neutral fluid in B leaving, so far as the phenomenon has yet been described, an unbalanced residue b equal to a; this residue is finally equilibrated in some way by the equal residue of opposite sign $-a$, which must have been brought into evidence when A was first charged. Equilibrium may be brought about by the actual combination of the residues $-a$ and b, or if these are insulated from one another the two residues will be held by induction oppo-

site one another. Or equilibrium may be attained partly by their combination and partly by induction between them. When equilibrium is established between two charges across a dielectric we may with equal propriety speak of either as inducing the other.

No charge of electricity can exist in equilibrium without an equal and opposite induced charge. The equal positive and negative charges and their dielectric are three inseparable parts of one phenomenon. The arrangement of these may be more complex than that described above; for instance, we may have several insulated bodies, some independently electrified and some not, all in one field, but in all cases each particle of positive fluid only exists in virtue of the existence of an equal particle of negative fluid, and these when at rest balance one another by induction across a dielectric or dielectrics.

§ 8. *Relation of Charge to difference of Potential. Capacity.*—Let a charged sphere A (fig. 2) of large dimensions be separated from the hollow sphere B by a comparatively thin layer of dielectric D; a test charge placed at any point in the dielectric will experience a force which is constant at all points of the dielectric. The work done in moving that test charge from B to A will be the product of that constant force into the distance between the shells. Now, conceive the charge on A to be doubled. The induced charge, the force on the test charge, and the work required to move the test charge from B to A, will all thereby be doubled. Therefore the difference of potential between A and B must have been doubled. Thus we see that the charge induced between A and B is proportional to the difference of potentials between them. This law holds good for any constant system, whatever be the shape of A and B or the material of the dielectric. If, however, the dielectric be changed,

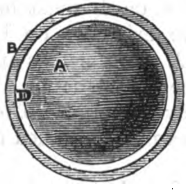

Fig. 2.

the charge corresponding to a given difference of potentials will also change. That quality of dielectrics in virtue of which the charge across one is greater than that across another is called their *specific inductive capacity*. The charge does not depend on the absolute potential of A or B, but merely on the difference of their potentials. If B is insulated and its potential raised or lowered the potential of A will rise or fall with that of B, and the charges on these opposed surfaces will remain constant. No charge outside the boundary between B and D can by induction alter the distribution of electricity inside that boundary.

Now, reverting to the consideration of simple large spheres separated by a small layer of dielectric, let us conceive the distance between A and B doubled while the charge on A remains unaltered. The charge on B will remain unaltered, and from the law in § 5 it is easy to show that the constant force which a test charge would experience at all points of a dielectric will also remain unaltered. The work to be done, therefore, in bringing a test charge from B to A has been doubled, and consequently the difference of potential between B and A has been doubled. To reduce the difference of potentials to that which we had at first we must halve the charge. Thus, with a constant difference of potential the charge on A or B is inversely proportional to the distance between them. In general the nearer two conductors of any shape are brought the larger the charge between them for a given difference of potential. The *capacity* of any conductor A in a constant system of two conductors A and B separated by a dielectric D is the quantity which A or B will receive when a unit difference of potential is maintained between A and B, or it may be defined as the constant quotient we obtain when the quantity on A is divided by the difference of potentials between A and B.

We may with equal propriety speak of difference of potentials between two conductors as the cause of the charge upon them; or of the charge upon the con-

ductors as the cause of the difference of potentials between them.

§ 9. *Comparison of Potentials.*—Differences of potential can be compared without the complex process of measuring work (§ 6). Let us place two conductors in a constant relative position with a constant dielectric, such as air, between them, and let us surround this system by an uninsulated shell so that no charge can be induced upon them from without. The charge on the two bodies will be proportional to the difference of their potentials. The force exerted between them will be connected with their charge, and therefore with the difference of their potentials, by a definite law. Thus if the two conductors be parts of large plane surfaces the force between them can from § 5 be shown to be proportional to the square of the difference of potential between the plates. By comparing the force observed on different occasions we can therefore compare differences of potential numerically. The instrument may be so graduated that from our observations the measure may be given in terms of the unit defined in § 6.

§ 10. *Density, Distribution, Tension.*—The *density* of a charge at any point is the charge per unit of area at that point. The density of the charge is uniform on all parts of two indefinitely large opposed plane electrified surfaces. The density is uniform over the surface of a charged conducting sphere when surrounded by a hollow concentric conducting sphere or when indefinitely remote from all other conductors. When the thickness of the dielectric between two opposed conductors is variable the density of charges induced between them tends to be greater when the conductors are near one another than when they are further apart. The density of any charge tends to be greater at all projecting edges or points and at all places of rapid convex curvature, than on concave, flat, or slightly curved convex portions of the surface. These statements may be verified by experiment or derived from the laws of induction and the law of force, § 5.

The electricity on any small area of an electrified surface is acted upon by a force normal to that surface. This force tends to stretch the conductor outward, or to tear off a part of its surface, and is called the *Electric Tension* at that place. Tension is measured in units of force per unit of area, and is proportional to the square of the density on the element of surface. A soap bubble expands when electrified under the action of electric tension.

The word tension has been used by various writers in various senses. The above interpretation agrees with the definitions given by Sir Wm. Thomson.

§ 11. *General Remarks. Convection, Sparks, Points, Silent Discharge, Brush, Glass.*—Convection is a term employed to describe the conveyance of electricity from one place to another by numerous small particles of matter charged with the electricity in question. Thus a charged conductor will be discharged by convection if steam or spray be blown to or from it; each globule of water leaving the conductor brings or carries away a charge of electricity.

When two conductors at very different potentials are brought close together one or more *sparks* will pass between them, conveying electricity from one to the other. The spark consists of white hot matter electrically charged. The disruption of this matter from the body is caused by electric tension. The heat and light observed are due to the mechanical action of disruption, as when a spark is struck by steel from flint. The spark is not electricity.

The electricity on a conductor charged to a high potential escapes into the air from any sharp *points* or edges on that conductor. The action is one of convection by a stream of particles producing an actual current in the air, and is due to the tension at the points or edges. When the action is unaccompanied by noise or light it is called a *silent discharge* from a point; when accompanied with noise or light the term *brush* is applied to the phenomenon. Either negative

or positive electricity may be discharged in this way. If two conductors are at sensibly different potentials a sharp metal point on either brought into the neighbourhood of the other will allow electricity to pass by silent discharge or in a brush from one to the other. Dust tends to discharge conductors both by direct convection and by its filaments, which act as points.

A conductor intended to retain a large charge or remain at a high potential must be clean, smooth, and without sharp points, besides being supported on a good insulator. *Glass* being a cheap material and an excellent insulator is much employed in electrical apparatus. Owing, however, to the fact that moisture from the air condenses readily on any cold glass surface, glass supports will not insulate well unless they are warmed. The moist film which forms on the surface of glass conducts electricity well, and being always present in moist air gave rise to the false idea that moist air was itself a conductor. The glass stems used to support and insulate conductors are usually coated with a varnish of shellac, a substance which attracts less moisture than glass does. Vulcanite is a good insulator for electrical apparatus and does not attract moisture so much as glass. All insulating supports, whether of glass, shellac, vulcanite, or other materials, must during experiments be kept clean and dry.

A metal point will draw off electricity from the surface of an electrified insulator in its neighbourhood, but the charge excited by friction on an insulator is not discharged instantly, or even rapidly, by bringing the surface of the insulator into contact with a smooth, flat, or rounded solid conductor. The electrically excited surface behaves as though the electricity were behind a thin insulating film, so that if a flat metal plate be placed on a flat disc of electrically excited glass or vulcanite a charge of opposite sign to that on the vulcanite will be induced on the surface of the metal plate where it touches the insulator. This curious phenomenon will be treated at length hereafter. The charge excited by friction on

an insulator will be wholly discharged if the surface be moistened, as by the breath, and then touched by a conductor.

CHAPTER II.

ELECTROSTATICS.

§ 12. *Attraction due to Induction.*—Let a small gilt pith ball be suspended by a dry white silk thread; a rod of vulcanite rubbed with silk or flannel, and thereby electrified, will visibly attract the ball if held near it. In this experiment the ball is made of pith that it may be light; it is gilt that it may be a conductor; it is spherical in order that electricity may neither pass to nor from it at sharp points or edges (§ 11); and dry white silk is used because it insulates. The vulcanite might be of any form, but a rod is convenient because it can be easily held, easily rubbed, and because the resistance due to its length tends to keep electricity at one end from passing to the uninsulated hand at the other. The attraction is very marked and easily observed when silk or flannel are used as the rubbers, but a similar effect will be observed if the vulcanite be rubbed with any dry substance. Any insulator may be substituted for the vulcanite, but a marked effect is more easily obtained with this substance than with most others.

The force between the ball and the vulcanite results from the following complex actions. The negative charge on the vulcanite, by induction, brings a charge of positive electricity to the near side of the ball, and repels an equal charge of negative electricity to the further side; the ball, being insulated by the air and silk, can neither part with electricity as a whole nor receive any. The charge on the vulcanite attracts the positive and repels the negative charge on the ball, but

the resultant force is an attraction, because the vulcanite is nearer to the positive charge than to the negative. If the surrounding conductors, such as the walls of the room and the person of the observer, be distant from the ball, the above actions describe the chief forces acting on the ball; but in all cases occurring under conditions which can be practically realised the ball is acted on by other forces due to the electricity on surrounding uninsulated conductors. This electricity, which, in the case taken, will be positive, leaks from the silk or flannel rubber to the earth, and distributes itself as an induced charge on the walls of the room and the other conductors surrounding the vulcanite and ball. Each portion of this positive charge repels the positive and attracts the negative electricity on the ball, modifying, moreover, the distribution on the ball. The effect of these forces will be slight if the ball is distant from all parts of the surrounding uninsulated shell; but if the observer place his hand near the ball on the opposite side to the vulcanite an increased deviation of the ball will show the action due to the positive charge induced on the hand, which repels the positive and attracts the negative charge on the ball; but repels more than it attracts, because the charges of the same sign are nearer than those of opposite sign. So long as the electricity is moving in the ball, we may conceive that the ball itself is not attracted; but after an inconceivably short time each particle of electricity influenced by the charge on the vulcanite reaches a position on the boundary of the insulated ball, where it will remain in equilibrium if the ball is held stationary; and if then the resultant force on the electricity is in a given direction this force acts to move the body itself in that direction, since the electricity cannot quit the body. This typical case represents the action of all electrically excited insulators on insulated conductors. The names of the electricities will be all reversed if glass is used in place of vulcanite, but the forces will be of the same kind. The experiment illustrates the fact that an electrified body

attracts all conductors, which are separated from it by a dielectric, in virtue of the distribution of electricity which it induces upon them.

§ 13. *Permanent Charges obtained by Induction.*— The potential of every point between the vulcanite and the earth (in which term all uninsulated bodies are included) is negative. The potential of the pith ball, under the influence of the charge on the vulcanite, is negative, and if therefore an uninsulated wire be allowed to touch the ball positive electricity will flow from the earth to the ball, bringing its potential thereby to zero. This positive electricity will be part of that which previously was induced on the walls of the room, as described in § 12. The access of positive electricity will increase the attraction between the vulcanite rod and the ball. When the wire is withdrawn the ball remains charged with an excess of positive electricity. The ball thus charged may be removed from the neighbourhood of the vulcanite, carrying positive electricity with it; when thus removed its potential rises, and the charge upon the ball will then flow to the earth if a connection be made between the ball and the earth. Any number of bodies may receive charges of positive electricity by induction from the single charge on the vulcanite. In the above experiment the result is not changed by changing the place where the ball is touched by the wire; positive electricity will flow to the ball whether the wire touches the ball where the negative charge was previously accumulated or where the positive charge was previously accumulated. The potential of the ball is uniform throughout, and is not sensibly changed by the approach of so small a body as the end of a wire. The direction of the flow of the electricity depends on the difference between the potential of the ball and that of the end of the wire, and not on the previously existing density or on the mechanical tension. If a large conductor be used instead of the wire its position will affect the result by affecting the potential of the ball as it approaches. When the ball is touched

by the hand, for instance, it is no longer a matter of indifference whether the hand intervenes between the ball and the vulcanite or not.

If glass be used instead of vulcanite similar results follow, but the signs of the electricities are all reversed.

The experiments above described show how conductors may by induction be wholly charged with electricity of either sign so as to keep that charge when removed from the influence of the inducing body. The experiments also illustrate the meaning of the word potential.

§ 14. *Force between Positive and Negative Charges.*—A pith ball positively charged, as above, repels another which is also positively charged. A pith ball negatively charged repels another negatively charged. Pith balls charged with electricity of opposite signs attract one another.

A pith ball positively charged by induction from the vulcanite is repelled by electrically excited glass. A pith ball negatively charged by induction from glass is repelled by electrically excited vulcanite.

§ 15. *Conduction.*—A pith ball which is allowed to touch electrically excited glass receives a positive charge by *conduction*, and is then repelled by the glass. A pith ball which is allowed to touch electrically excited vulcanite receives a negative charge by *conduction*, and is then repelled by the vulcanite.

One charged pith ball gives by conduction a portion of its charge to any other uncharged ball brought into contact with it. An electrical charge acquired by conduction does not differ in its qualities from a charge of the same kind acquired by induction.

The gradual diminution of electrical effects produced by an electrified rod of glass or vulcanite is due to the gradual conduction of the electricity from the rod to the hand and thence to the earth, where it neutralises a corresponding quantity of the electricity which it previously induced. This slow conduction, whether through

an insulator or through the damp film on its surface, is often called *leakage*.

§ 16. *Effect of Screens.*—If a large uninsulated conducting screen, such as a sheet of metal, be placed between a suspended pith ball and an electrically excited insulator, or a charged conductor, no force will be observed between these bodies. If the screen be insulated the force will still be decreased if the screen be a large flat sheet; but if instead of this form we interpose a comparatively small rounded conductor, the force will on the contrary be increased; the effect of an *insulated* screen depends on its form and dimensions relatively to those of the two other bodies. In the first case the screen will be charged on the side next the inducing body, say electrified glass, in such a manner that for all points behind the screen the combined effect of all the electricity on the glass is neutralised by the effect of all the electricity on the screen. This exact neutrality follows from the fact that all points of the screen are at zero potential; it is therefore clear that a "test charge" (§ 6) will experience neither resistance nor assistance in being brought up to the back of the screen. In the second case the side of the screen next the glass will be charged with negative electricity, but the further side will be charged with an exactly equal quantity of positive electricity. The potential at the two boundaries of the screen and throughout the screen will be identical, but will not be zero. The screen has the potential depending on its position between the glass and the earth.

§ 17. *Induction and Conduction between an Electrically Excited Insulator and Bodies in contact with it.*—The forces of attraction and repulsion described as existing between pith balls are exerted similarly between all conductors charged with electricity, but these forces are usually so small that their action is not evident except in cases where they meet with small mechanical resistance. The same remark applies to the forces between conductors and electrically excited insulators. It is for this reason that in the following experi-

ments light bodies, such as paper and metal foil, are chosen.

If a rod of vulcanite be electrically excited and immediately afterwards held over a small piece of crumpled paper lying on a wooden table, the paper will fly up to the vulcanite, remain attached for a little while, fly back to the table, remain at rest for a little while, and then repeat the movements at longer and longer intervals, until the electricity on the rod has leaked away.

The negative charge on the vulcanite induced a positive charge on the paper and on the table near it. This charge was most dense on the projecting crumpled edge of the paper. The attraction between the charges caused the paper to spring up charged with an excess of positive electricity; as soon as it reached the rod negative electricity began to pass from the rod to the paper across the sharp edges where the paper touched the rod. At these points the density and consequent mechanical tension were sufficient to break across the insulating film spoken of in § 11. The resistance of the vulcanite, which is an insulator, and of the paper, which is a bad conductor, delayed the passage of the negative electricity; but when this had arrived in sufficient quantity, the paper was repelled by the vulcanite and attracted by the table, from which, under the influence of the charge on the vulcanite, it again slowly received positive electricity so as to be again attracted by the vulcanite.

If the paper after flying back from the vulcanite is received on an insulating body, such as a sheet of clean, dry glass, it will not be again attracted by the vulcanite, for it will retain the negative charge which it received.

If a piece of metal foil be substituted for the paper the alternations of motion will take place more rapidly, for the conducting power of the metal facilitates each successive redistribution of electricity. Often the motion will be reversed before the foil touches either

the vulcanite or the table. The electricity, by which in these cases the charge on the foil is continually reversed, passes to and from its edges in the form of a brush or silent discharge.

When the potential to which the vulcanite is charged is not high, the foil will *cling* to the vulcanite, instead of springing to and fro as described above. When clinging in this way the foil is charged with positive electricity by induction across the insulated film. The mechanical tension, due to the difference of potential between the vulcanite and the foil, is in this case insufficient to break across between the two opposed *surfaces*. If under the same circumstances a conducting *point* or edge be brought against the vulcanite it will receive negative electricity by conduction; thus a little hollow cylinder of gilt paper which usually strikes with its edge will spring backwards and forwards between the table and a rod of vulcanite to which at the same time a piece of flexible foil is clinging. The stiff cylinder is charged negatively by conduction or convection from the very same body which charges the flexible foil positively by induction. The table on which these experiments are tried should not be a very good conductor, or the foil and paper will sometimes not spring to the vulcanite, but merely stand on edge and neutralise the opposite electricity by a silent discharge.

§ 18. *Insulators are not attracted by an Electrical Charge.*—If a thin slice of fine black india-rubber be freshly cut with scissors or a knife, and allowed to fall on the table without being touched by the hand, it will neither be attracted nor repelled by an electrically excited rod of vulcanite or glass. In an insulator the positive and negative electricities cannot separate and distribute themselves as described in the case of the conducting metal foil or the imperfectly insulating paper. Thus the india-rubber, being an insulator, cannot be inductively charged, and is neither attracted nor repelled by a charged body. If, however, the surface of the slice be damped or dirtied, so as to

conduct a little, the india-rubber will behave as the paper did. As india-rubber is not a perfect non-conductor, in course of time, if maintained under the influence of a charge, it will come to be charged, and will then be attracted.

§ 19. *The Electrophorus.*—The electrophorus is a simple apparatus used to obtain electricity in considerable quantities, and at a high potential. It consists (fig. 3) of two parts. 1st, a plate A made of some good insulator, supported by a conductor B. 2nd, a conducting disc C, with an insulating stem D. The conductors are conveniently made of brass, and the insulators of vulcanite; but wood coated with tinfoil and a cake of resin will answer the same purpose. If the surface of A be rubbed with silk, flannel, or even a dry hand, and the disc C be placed flat on A, this plate will be electrified by induction in the same manner as the metal foil which clung to the vulcanite rod (§ 17). The insulating film (§ 11) on the surface of A acts as a dielectric across which electricity does not pass by conduction, by spark, or by silent discharge.

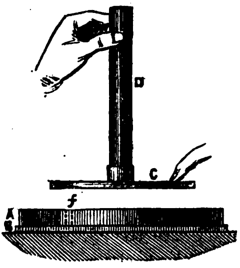

Fig. 3.

The potential of C falls below zero under the influence of the negative charge on A, and if C be now touched by the finger the potential of C will be raised to zero by the influx of a positive charge. This charge is attracted by the opposite charge on A to the lower face of the disc C, leaving the density elsewhere sensibly nil; if the finger be now removed, and the disc C lifted off the vulcanite, the positive charge will distribute itself over the whole surface of the disc, the potential of which will rise so that it will be ready to communicate its positive charge to any other conductor at a lower potential, such as the finger, which, if now brought near the edge where the density is

greatest, will receive the charge in the form of a spark. The disc C is charged in exactly the same way as the pith ball of § 13, but in one case the dielectric consists of a considerable thickness of air, and in the other case it is a mere insulating film. If the disc C be replaced on A, again touched with the finger, and again removed, a second spark can be taken from C without any fresh excitation of A. This operation may be repeated an indefinite number of times in rapid or slow succession. The disc C may be used to charge a conductor F (not shown in the figure) to a high potential by a succession of sparks. If F be well insulated each successive spark will be shorter than that which preceded it, for the difference of potential between C and F will be decreased by the electricity which each spark conveys. When F has been charged all the electricity given it can be drawn off by a single touch (except such as may have leaked away by the insulating stem or by brushes). With the help of the electrophorus and a conductor F of large capacity we can obtain and store up a considerable quantity of electricity at a high potential, with which we can produce more intense electrical effects than any which have so far been described.

The spark from F as it is discharged will be large and brilliant, and if passed through the hand will produce the feeling known as an electric *shock*.

The charged disc C of an electrophorus, held over pieces of paper or foil on a table, will make these spring up and fly off as the excited vulcanite did, but the pieces of foil will never adhere to the metal conductor, for no insulating film occurs between two conductors. The pieces of paper adhere for the time required to allow these imperfect conductors to receive a sufficient quantity of electricity from C to neutralise their previous charge.

If the disc C of an electrophorus, instead of being placed flat on the electrically excited surface of A, is drawn across that surface so as to scrape it with one edge, the disc will be negatively electrified by con-

duction or convection, instead of being, as before, positively electrified by induction. When the sharp edge of C is presented to A the tension produced by induction is sufficient to break through the insulating film. We have here an experiment showing that a body can be charged positively or negatively by contact with the same electrified insulator, the sign depending on the manner of the contact, whether by a flat surface or by an edge. Any dry substance, whether it be a conductor or an insulator, will electrify the plate A when rubbed against it. Experiments showing this may be easily made by using as a rubber a soft pad thinly covered with the substance to be tested. If the pad is fixed on an insulating handle, an electroscope (§ 22) will show that the pad is electrified as well as the vulcanite, and that the electrical charges on the two substances rubbed together are of opposite signs.

§ 20. *Distinction between Potential, Density and Tension illustrated.*—A small conducting peg *f* (fig. 3), running through the vulcanite from its upper surface to the conductor B, is generally and conveniently made to do duty for the touch of the finger at each successive application of the disc C. Surprise is sometimes felt by those who have not grasped the idea of potential that this peg can serve for the discharge of the negative electricity, which, before C is joined with the earth, forms a charge on the upper side of this disc. It is easily seen that a flow of positive electricity *to* C is equivalent to a discharge of negative electricity *from* C, but a difficulty is felt in understanding how positive electricity can flow up to the face of the disc which before the introduction of *f* is everywhere charged positively, and where an actual mechanical tension exists tending to expel particles charged with positive electricity. We may, however, even without using the idea of potential, understand the function of *f* by considering the series of actions and reactions which would occur if this uninsulated peg were introduced after the insulated disc C had been placed on A. If A forms an

unbroken plate of vulcanite there will be a tension due to negative electricity over the whole of the upper face of A, and a tension due to positive electricity over the whole of the lower face of C. If we now conceive a hole made in A for the peg *f*, the tension on the lower face of C will grow less opposite this hole; and if the uninsulated peg *f* be then introduced, the density on C opposite the peg will gradually diminish as the peg gradually approaches C; for the combined action of the negative electricity on A and the positive electricity on C will produce a resultant force charging the top of *f* with positive electricity. This charge will be so dense before *f* touches C as to drive all positive electricity away from those parts of C which are opposite *f*, and finally to create a new tension due to negative electricity, which *f* induces. The other parts of the lower surface of C will remain charged with positive electricity, and there will be a ring concentric with *f* between the negative and positive charges where the density and tension are zero. It is now easy to see that when *f* touches C no positive electricity will be driven off, but that the resultant force due to all parts of the charges on A and C will draw up positive electricity and repel negative electricity through *f* until the negative electricity has all flowed away, or is neutralised, and the positive electricity on C is equal in quantity to the negative electricity on A.

The action is thus explained by the fact that the original positive tension on the surface of C was, opposite *f*, done away with by the very introduction of that peg. The actions have been followed in detail to illustrate the complete fallacy of the idea that electricity will always flow from a surface where there is a tension due to the presence of positive electricity if an uninsulated conductor is brought up to the spot. The very action of bringing the uninsulated conductor near the surface may, as in the above case, reverse the sign of the electricity present.

§ 21. *Electrical Machines.*—The name electrical

machine is given to apparatus for producing a continuous supply of electricity by means of a plate or cylinder of some insulator made to revolve between rubbers, by which its surface is continually excited. Glass and vulcanite are the materials commonly employed for the plate or cylinder, and the electricity is usually collected upon an insulated *conductor* of considerable capacity by metal rods led from it and armed with points which nearly touch the electrically excited body shortly after it leaves the rubbers, which in this arrangement are themselves uninsulated. When vulcanite is used, the negative electricity with which this body is charged by friction flies from its surface to the points and charges the conductor; an equal quantity of positive electricity flows from the rubbers to the walls of the room, and is held there in equilibrium by induction from the conductor. When glass is used instead of vulcanite the motion of the electricities is reversed. Electricity will be equally well collected if we connect the rubbers with the conductor and the points with the earth. It is essential that the points and the rubber should be respectively connected with the two conductors upon which the two opposed electricities are held by induction across a dielectric. One of these two conductors is usually the main conductor of the machine, and the other the uninsulated walls of the room or the earth, but any two conductors separated by a dielectric might be used, and both might then be insulated from the earth, which in all these experiments must be regarded simply as a large conducting body, having no special property except its size to distinguish it from other conductors. The quantity of electricity collected on the conductor of a machine depends on the difference of potentials produced by the friction between the rubber and the insulator, and on the *capacity* of the conductor, which may be of large dimensions. A long tin tube with hemispherical ends may be used for this purpose, or a pasteboard tube with rounded wooden ends, the whole

covered with metal foil. Thorough smoothness of surface is desirable to prevent leakage by brushes from projecting points. The supports should be long, small, dry, and perfectly clean. When glass is used as the body to be excited the rubbers are commonly leather pads, on which is spread a thin coating of amalgam formed of one part of tin and two of mercury. The advantage of the amalgam probably consists simply in the fact that it is a good conductor, and so allows the electricity of opposite sign to that on the glass to pass readily away. The collecting points must obviously be placed at some distance from the rubbers, each of which is provided with an oiled silk flap covering the electrically excited surface between the rubber and the collecting points. The function of these flaps is to prevent the passage of sparks or brushes between the electrically excited surface and the rubbers. This they effect by their mechanical resistance to disruption; for the tension, which would be sufficient to break through the air, is insufficient to break through the solid oiled silk. Dryness and cleanliness are essential to the working of an electrical machine. Let it be noted that the electricity collected by the points is always of the same sign as that on the excited surface.

§ 22. *Electroscopes.*—Fig. 4 shows the simplest form of electroscope, or instrument by which the presence of electricity is detected. Two pieces of gold leaf, *b*, *b*, hang side by side from the metal cap *d* by the rod *a*; the cap is supported by the glass cylinder *c*, inside which two strips of uninsulated metal foil are placed opposite *b* and *b*; or, what is better, the whole internal surface of the glass is covered by a screen of metal network, which prevents uncertain and unknown charges from accumulating on that surface, and in common with the cap *d* preserves the gold leaves from the

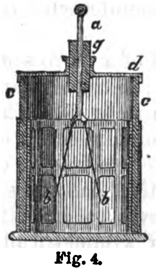

Fig. 4.

direct attraction or repulsion of electricity outside the instrument. The rod *a* is insulated by the vulcanite *g*, through which it passes, and commonly has a knob or ball at its upper end. The body we wish to examine is brought near this ball, and if charged, say, with positive electricity, it increases the potential of *a*, induces a negative charge on the ball and a simultaneous positive charge on both *b* and *b′*, which then diverge under both the repulsion between the two similar charges which they receive, and the attraction for the opposite induced charge on the uninsulated metal foil. If while the leaves diverge we touch the ball, the potential, which was positive, is by the influx of negative electricity brought to zero, and the leaves fall together; if we next remove the finger and afterwards the electrified body, the potential of the leaves falls still further, and they are left charged with negative electricity, under the action of which they again diverge. If a positively charged body is then brought near the ball *a* the divergence of the leaves will diminish. The influence of a negatively charged body will, on the contrary, increase the deflection. In the Peltier electroscope, in place of the gold leaves we find a fixed metal ball and a little horizontal conducting index pivoted so as to be repelled by the ball through a greater or less number of degrees according to the density of the charge on the ball and index. The repulsion is counteracted by a small magnet fixed to the index.

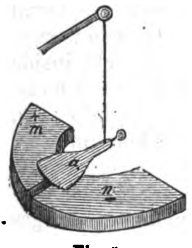

Fig. 5.

The essential parts of a more sensitive instrument, due to Sir William Thomson, are shown in fig. 5. The light, flat, broad aluminium index *a*, highly charged with electricity of known sign, say positive, hangs by a metal wire which serves to direct it by torsion over two symmetrically placed flat insulated conductors, *m* and *n*; when these are both at one potential the induction from the index

is the same on both sides, and it remains in the zero position as directed by the wire, that is to say, with its central line vertically over the narrow slit which divides *m* and *n*. When, however, the potentials of *m* and *n* differ induction takes place unequally; in the case supposed, the conductor which is at the lower potential will receive the greater negative charge, and the index will deflect to that side. The direction and amount of the deviation indicate the nature and amount of the difference of potentials. In using the instrument it is usual to keep either *m* or *n* connected with the earth or at zero potential. The deflections are then proportional to *the* potentials of the other conductor so long as the electrification of *a* is constant. The higher the potential to which *a* is electrified the more sensitive the instrument. Very careful screening is required with electroscopes of this type.*

§ 23. *Leyden Jar.*—For many purposes conductors of large capacity are required; we found (§ 8) that this capacity depended on three elements: 1st, the surface of the conductor; 2nd, its distance from an opposed conductor; and 3rd, the dielectric separating the two. It is more convenient usually to diminish the distance between the two opposed conductors than to increase their surface; but as we decrease this distance we shall, when the difference of potential between them is great, produce great density on the opposed surfaces, and consequently great mechanical tension. If the dielectric be air, sparks or brushes will then occur, and by their action limit the difference of potentials which we can maintain. If for air we substitute glass, or some other solid insulator, this convection will be stopped, and at the same time the capacity of the opposed conductors will be increased, for the inductive capacity (§ 8) of air is almost the smallest known.† The Leyden

* These instruments are called electrometers when adapted not merely to indicate, but to compare numerically, differences of potential.

† Hydrogen, according to Boltzman, Ayrton, and Perry, falls even below air.

jar (fig. 6) is an apparatus designed, in accordance with these principles, to give conductors of which the capacity is large relatively to their surface: metal foil coatings A and B, inside and outside a glass jar D, form the two opposed conductors, separated by a thin solid dielectric; the upper portion of the jar is uncoated, and must be kept clean and dry to insulate the one coating from the other; the top is closed to give a support to the rod; the stopper is otherwise useless and indeed injurious; sometimes a special drier, such as concentrated sulphuric acid, is placed in a vessel inside the jar. The inner surface of the glass can in this way be kept clean and dry, but there is always a slight film of damp and dirt on the outside. The stopper where it touches the rod F connects the inner coating with this film, and must be omitted when very good insulation is required. The jar is then charged through a temporary rod held by an insulating handle, and withdrawn as soon as the desired charge has been given. When these precautions are taken a good jar will not lose more than one per cent. of its charge per diem. In the ordinary jar with a fixed rod F, the neck may be usefully coated with shellac varnish, on which moisture is not so freely deposited as on glass. Some varieties of glass insulate more perfectly than others, and defective or cracked glass may cause leakage after every precaution has been taken to ensure dryness and cleanliness.

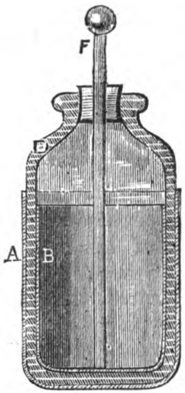

Fig. 6.

If a number of jars have their inner coatings connected and their outer coatings connected, but the inner and outer coatings insulated from one another, the system, which is called a *Leyden battery*, will act as one large jar, having a capacity equal to the sum of the capacities of the jars employed.

The inner and outer coatings of a charged jar contain equal quantities of electricity of opposite signs wholly distributed over the surfaces where the coatings touch the glass. On these surfaces the density and tension are great, so much so that if the glass be too thin a spark will pass from one coating to the other and crack the jar; there is no electricity or tension at the surfaces where the coatings touch the air.

A jar may be charged by any means which will produce a difference of potentials between the inner and outer coatings. The most usual method is to let sparks from the disc of an electrophorus, or from the conductor of an electrical machine, pass to the inner coating, while the outer coating is uninsulated. The sparks then raise (or lower) the potential of the inner coating, and produce a considerable difference of potential between the inner coating and the outer coating, which latter, being uninsulated, remains at zero potential. When sparks cease to pass we know that the inner coating has been brought to the highest potential possible with the given source of electricity. If sparks continue to pass to a Leyden jar in indefinite numbers, that is a sign that the electricity is leaking from the inside to the outside coating. The inner and outer coatings are identical in the functions they perform, and may be interchanged in any experiment; but owing to the form of the jar it is more convenient, when we desire that one coating should be uninsulated, to let the outer coating be that which is connected with the earth.

The charge of a Leyden jar cannot be altered except by simultaneously altering the charges on the two coatings. While the charge on either coating remains constant, that on the other coating will remain unaltered, and consequently the difference of potentials between the coatings will remain unchanged. Thus if, when a jar has been charged as above described, the outer coating be insulated, the inner coating may be joined to the earth, or to the most highly electrified body, without producing any alteration in the charge

of the jar.* When the coatings are joined by a conductor the opposite electricities are at once neutralised, the potentials of the coatings become equal, and the jar is said to be discharged.

The Leyden jar or battery, by storing a considerable quantity of electricity at a high potential, facilitates many striking experiments. A shock is felt if the discharge passes through any part of the experimenter's person, and a simultaneous shock will be felt by a large number of people if they form an important part of the conductor employed to join the two coatings. The shock may be so intensified, by increasing the capacity of the jars, as to be dangerous and even fatal. The connections required to discharge a Leyden battery are therefore usually made by metal rods held in an insulating handle. A large and brilliant spark accompanies the discharge of a jar, for the tension on the opposed parts of the conductors used for the purpose is sufficient to break through the air before their contact is completed. This spark may be made to pass across a series of interruptions which all appear simultaneously illuminated. Many beautiful experiments with Leyden jars and electrical machines will be found described in all older treatises on electricity. The student will find a useful exercise in analysing the observed effects according to the principles laid down in the present book.

Leyden jars of large capacity, but adapted only for moderate differences of potential, are made with sheets of foil separated by thin mica plates or paper prepared with paraffin. Systems of this kind are usually termed *condensers.* They are sold by opticians arranged in graduated series. The form of the condenser is extremely different from that of the Leyden jar, but the principle of its action is the same.

It should be noted that the charged surface of every conductor may be looked at as one coating of a system analogous to a Leyden jar (*vide* § 7). Mathematicians,

* This would only be absolutely true if there were no projecting knob.

indeed, investigate the laws of distribution on bodies supposed to be hung in an infinite insulating field, but these calculations simply refer to the case in which the oppositely charged conductor is at an indefinitely great distance.

§ 24. *Distribution of Electricity.*—Case 1. A constant system, consisting wholly of the surfaces of two conductors separated by a dielectric, has a definite measurable capacity, which may be called the capacity of the system, or of either conductor; each element, or arbitrary sub-division of the surface, has also its definite capacity. Whatever may be the difference of potentials between the conductors, the relative quantities of electricity on the elements will be proportional to the capacity of each element. The surface of the conductor at the higher potential will, over the whole boundary separating it from the dielectric, be charged with positive electricity; and the surface of the conductor at the lower potential will, over the whole boundary separating it from the dielectric, be charged with negative electricity. The Leyden jar and condenser afford instances of this kind of distribution. If two systems such as this, each so complete in itself as not to be affected by any other bodies in the neighbourhood, be joined so as to form only one system, the charge which they contained will be re-distributed in such a manner that the relative charges on the several elements will be proportional to their several capacities. This takes place when the coatings of two Leyden jars are joined in pairs by conductors of no sensible capacity. Case 2. Let there be two insulated conductors A and B (fig. 7) in one dielectric, such as air, and enclosed by a conducting shell C, such as the walls of a room. For any given position of A, B, and C, these bodies will have a definite capacity depending partly

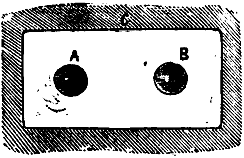

Fig. 7.

on the relative position of A and B. Let A and C be fixed relatively to one another, and charged with equal and opposite quantities of electricity, the distribution of these depends partly on B, and if the position of this body is changed the whole electric field will be modified. The charges on A and C will remain constant, but the capacity of these conductors and of each of their parts will change, and the distribution of the charge will change. (The difference of potentials between A and C will also alter.)

When B is brought into contact with A the charge on A will be shared with B, but we cannot determine in what proportion by any rule similar to that given in case 1 (when two complete systems suoh as Leyden jars are joined), for neither A nor B have any fixed capacity irrespective of their relative positions. A and B when in contact become one conductor, the distribution on which depends on its shape and its position relatively to C. The sign of the electricity taken by B, if previously uncharged, will, however, always be that of the electricity on A; and if B be small and of such shape as not materially to alter the form of A when the two are in contact, B will receive a portion of the charge on A proportional to the density at the point where contact takes place. B can then be removed, and the sign and amount of this charge examined by aid of an electrometer. A small conducting disc on an insulating handle is often used in this way to investigate the distribution of a charge on a large conductor, and is called a *proof plane*. The observer must bear in mind that the position of his own body modifies the form of C, and influences the distribution. Case 3. Let there be two insulated conductors A and F in one dielectric, bounded by the shell C (fig. 8); let A and C be charged as before; let F be fixed relatively to A and C; and let the problem be the experimental investigation of the distribution of the charge on F under the influence of the bodies A and C. If a movable insulated conductor B, also enclosed in the shell C, be brought into contact

with F, the distribution on B and F will be that produced on the compound body by induction in the then existing field; if B be a proof plane it will neither sensibly modify the elec-

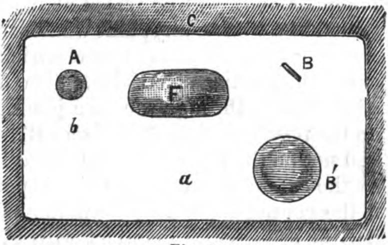

Fig. 8.

tric field nor the form of F, and will receive a charge proportional to the density of the point where it is tangent to the surface of F; and, being removed, may be examined by aid of the electrometer, as in case 2. If A be charged with positive electricity, and F was previously uncharged, the end near A will be found charged with negative electricity; the part nearer C with positive electricity; and a line separating those two regions with neither. (The potential of F will be positive and uniform throughout.) If instead of a small proof plane a large uncharged conductor B′ be introduced into the field, a change in its position will so materially affect the distribution on F that the charge received by B′, when brought into contact with F, gives no information even as to the sign, and much less as to the density, of the charge at the place of contact on F before B′ was brought near. This will be equally true whether the whole mass of B′ be brought near F or only a small part of that mass, such as the end of a wire, for the end of this wire necessarily has the potential of B′; thus, if in the present case B′ be introduced into the field near C, in the position marked by the letter *a*, its potential will be lower than that of F; and if connected by a wire with *any* part of F, B′ will become wholly charged with *positive* electricity, leaving F charged with an excess of negative electricity. This change of distribution brings F and B′ to one potential. If, on the contrary, B′ be placed nearer to A than F is as at *b*, the

potential of B′ will be raised above that of F, and when joined by a wire to any point whatever of F, B′ will become wholly charged with *negative* electricity, leaving F with an excess of positive electricity. The direction of the flow of electricity through the wire joining B′ with F depends on the position of the large body B′ relatively to A and C, and not on the point of F, which may happen to be touched by the connecting wire. This proposition is equally true if the connecting wire be infinitely short, that is to say, if B′ be brought into contact with F. Observers should remember that a change in the position of their own person, and especially of their hand, affects the distribution of electricity during these experiments.

§ 25. *Conduction.*—Let two electroscopes be used to indicate the potentials of B′ and F (fig. 8) respectively, and let B′ be joined with F by a well-insulated wire. It will be found that, *whatever be the length of this wire*, any change in the potential of F, whether produced by induction or by conduction from A, will be indicated simultaneously by the two electroscopes: the whole conducting system will, after the change, come to one potential in a period too short to be appreciated by the eye. If an imperfect conductor be substituted for part of the wire between B′ and F, a sensible time will be required before the full effect of a change in F is communicated to B′; that is to say, before the whole system comes to one potential. If a perfect insulator be interposed between B′ and F, as when the wire breaks and the broken ends are separated by air, a change in the potential of F will not produce an *equal* change in that of B′. A change in F may produce some change in B′ by induction across the interposed insulator, but the two conductors will not come to one potential. A good conductor opposes no resistance capable of sensibly delaying the distribution of electricity; an imperfect conductor resists so as to delay but not to modify the final distribution; and an insulator prevents the distribution from extending beyond the surface where it bounds a conductor.

§ 26. *Accumulation of successive Charges brought by Charged Conductor inside a Shell.*—If an insulated conductor B (fig. 9), charged, say, positively, be introduced inside a previously uncharged insulated conducting shell G, but not touching it, the interior surface of G will be charged with a quantity of negative electricity equal to that on B, and the exterior of G will be charged with an equal quantity of positive electricity. The position of B inside G will obviously not affect the amount of these charges; it will affect the distribution on the interior surface of G, but on the exterior surface of G the distribution will be unaffected by the position of B being determined by the form and position of the opposed surfaces of G and the surrounding shell C (not shown in drawing). Changing the position of B inside G will not affect the potential of G. If B is allowed to touch G the opposite charges on their opposed surfaces will cancel one another, leaving G wholly charged with a quantity of positive electricity equal to that originally on B. Let B be now withdrawn, recharged and reintroduced without touching G, a negative charge will again appear on the interior of G, and a new positive charge will be added to that already on the outside of G; if B now touches G the opposed charges on the opposed surfaces will again cancel one another, leaving two positive charges on the exterior of G; this process can be repeated any number of times, so that we can give G an indefinite number of charges from B by making the contact between the two bodies when B is wholly inside G. Each charge added raises the potential of G, which may be raised in this way indefinitely above that to which B is charged by the source of electricity. This does not involve the flow of electricity from a body of low to a body at high potential.

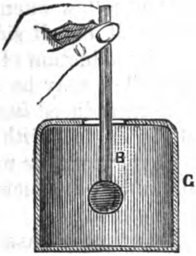

Fig. 9.

In bringing B towards G, while both bodies are charged, say, positively, we must do work to overcome their repulsion, and by the time G has passed inside B we shall have done sufficient work to have raised the potential of B, however low originally, above that of G. Results approximately similar to those described follow when G approximately encloses B, surrounding it on all sides except where an opening is left for the introduction of B. The effect of the series of events described may be expressed by saying that a charged body introduced *inside* a conducting shell, and then brought in contact with it, gives up its charge wholly to the shell, whatever may have been the relative potentials of the two conductors before the one was brought inside the other.

§ 27. *Induction Machines.*—The particular case of distribution described in the last paragraph has been taken advantage of in the construction of a very useful class of machines, which give an unlimited supply of electricity obtained by induction from a conductor, the original charge on which may be very small. Let the fixed hollow conductor A (fig. 10) be charged with, say,

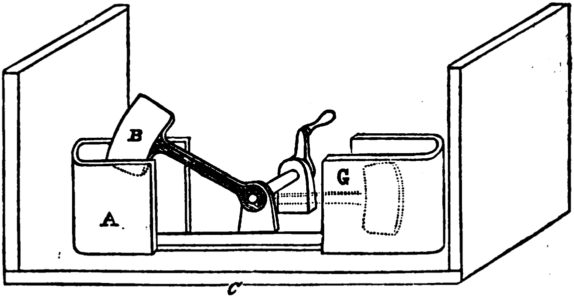

Fig. 10.

a small charge of negative electricity, and let the movable conductor B be electrified inductively (§ 7) by being placed near or inside A, and connected for a moment by a wire with the body C at zero potential.

This body, which acts as a conducting shell containing the whole system, may be the walls of the room. Next let B be insulated, then cross with its positive charge to the dotted position inside G, and be placed in contact with it for a moment; B will give almost all its charge to G (§ 26). Next, let this contact be broken, and B joined momentarily to C; B will then receive a negative charge by induction from G (§ 7); let the contact between B and C be now broken, and let B be replaced inside A and then joined to it, the negative charge on B will be given up to A, increasing its previous negative charge and lowering its potential. Let the above series of operations be called one cycle. It is clear that if we repeat this cycle we shall add a second positive charge to G, and a second negative charge to A. Moreover, the charges added during the second cycle will be larger than those added during the first. By continually repeating the cycle of operations we shall increase the charges on G and A, with no other limit than that due to the inability of the dielectric to prevent communication between the several conductors by sparks and brushes. We may then, while we continually repeat the cycle of operations, draw a constant succession of sparks from G if we take care not to let the conductor which receives them come into actual contact with G, or even very close to it, otherwise the potential of G may be so much lowered that it will not induce a sufficient negative charge on B to make up for inevitable losses which A sustains by leakage. The Holtz electrical machine depends for its action on the principles described in this paragraph.

§ 28. *Atmospheric Electricity.*—The atmosphere is at all times and places electrified, the difference of potentials between various parts at no great distance being often considerable. In fine weather the air is usually positively electrified and the earth negatively electrified by induction. Little is known as to the cause of this electricity, which appears to exist as a charge on very numerous small particles, the nature of which is not as yet ascertained.

A jet of water breaking into spray as it leaves a metal nozzle rapidly makes the potential of the nozzle, and of any insulated conductor to which it is attached, uniform with the potential of the surrounding air; for, when the potential of the conductor differs from that of the air, each drop of the spray carries away part of the electricity of the conductor as a charge. A flame connected with an insulated conductor produces the same effect as the spray, but the manner of its action is uncertain. A simple sharp point in connection with an insulated conductor will bring it by degrees to a potential which differs very little from that of the surrounding air, for if there be a difference of potential the tension on the point causes the electricity to break away as a brush or silent discharge. Thus one insulated conductor can be charged from another by means of a point on either without actual contact. It seems probable that the action of spray described above affords a rough illustration of what takes place during the silent discharge from a point.

An insulated conductor brought to the potential of the air by any one of the above methods can be examined by aid of an electrometer, and the potential of the atmosphere at any place can thus be ascertained.

§ 29. *Lightning.*—The difference of potentials between two portions of the atmosphere at a distance, or between a portion of the atmosphere and the earth, is sometimes sufficient to cause a disruptive discharge. The spark which passes is called lightning, and the mechanical violence done by its passage through the air produces the sound called thunder. A thunder-cloud is a cloud highly charged with electricity, and this cloud affects the earth beneath it in the same way as any other large well-insulated and charged conductor, that is to say, it charges the earth's surface by induction with electricity of opposite sign to its own. The density of this charge is greatest on those parts of the surface which project; the tension due to this density tends to produce a disruptive discharge, and lightning, therefore, most fre-

quently strikes some prominent object, such as a house or tree. Sharp points or edges on the projecting object will relieve the tension by a silent discharge, and will act as safety valves; the protection afforded by lightning conductors depends on this fact. A lightning conductor is a stout metal rod or rope having sharp points at its upper end reaching into the air above the object to be protected, and connected at its lower end with the earth by a large plate or other mass of metal buried in damp soil or water. When a thunder-cloud passes over a lightning conductor the electricity induced on the earth escapes in a copious discharge from the points, neutralising the electricity of opposite sign in the air, so that the flash of lightning is usually prevented. If, however, the electricity of the air is in quantity too great to be neutralised in this manner, lightning will pass, but will start from or arrive at the metal points, and will follow the conductor to or from the earth, doing no injury, provided the dimensions of the conductor are sufficient and its connection with the earth thorough. Mechanical injury is done by lightning only when resistance is met with. Lightning conductors should be fixed under the supervision of skilled persons, and they should be inspected from time to time, otherwise they may prove a source of danger. A tree acts as an imperfect lightning conductor; it has sufficient prominence, and conducts sufficiently well to attract the stroke, but resists the passage of electricity so much as to suffer injury when struck.

Frequently lightning passes from cloud to cloud, and does not strike the earth; in this case living beings on the earth may be injured by the sudden release of the charge which a cloud had induced on their bodies before the lightning passed. The presence of this charge is unfelt, but the sudden discharge acts as a shock from a large Leyden jar, and may be fatal.

The duration of a flash of lightning is less than one ten thousandth of a second; the light it gives is due to incandescent particles of matter, as in the case of all sparks.

§ 30. *Energy. Professor J. C. Maxwell's Theory.*—In any balanced system of electrical distribution the electricity exists in equal and opposite quantities, requiring therefore for its manifestation at least two conductors, separated by at least one dielectric. A complete system of this kind may be called an *induction pair*, requiring in its simplest form two equal and opposite stresses—one by which the oppositely electrified parts are drawn together, and a second by which they are held asunder. The most complex electrical distribution may be conceived as built up of charges producing numerous simple pairs of these equal and opposite stresses, resulting in a finite number of resultant pairs. The stress holding the parts asunder is a mechanical reaction due to the elasticity of matter, and is analogous to the stress in a loaded pillar or strained strut. The stress pulling the parts together is that due to electrical attraction, and may be conceived either as due to action at a distance, or as a stress in an imponderable medium occupying the same space as the dielectric. This second view is that advocated by Professor J. C. Maxwell, who has shown how certain optical and electrical phenomena are numerically connected, both in fact and on the hypothesis that both are due to modifications of one imponderable fluid, which, moreover, may be conceived as forming part of the mechanism by which gravitation is produced.

Each induction pair represents a store of energy; for the attraction between the opposed electricities is capable of performing work if the balancing stress be removed. The total work which each pair, however complex, can perform, in virtue of its electrical charge, is definite, being the sum of all the amounts of work which each elementary quantity of electricity would perform in passing from its own position and its own potential to a place of zero potential. *Elementary* quantity here signifies any quantity, small or large, having a uniform potential in the original pair. *Zero* potential is in the

above to be understood as that potential which all conductors of the induction pair would have if joined by conducting wires too small to affect the potential.

Since each induction pair represents a store of energy, work must be done to separate the equal and opposite electricities into that distribution which exists in the pair, that is to say, work must be done in the process of electrification, however that may be produced. The mode in which the energy of a pair is stored up is probably analogous to that in which the energy due to the elasticity of matter is stored up, that is to say, it results from a state of stress in a medium which, however, in the case of electricity, must be considered as an imponderable medium. On this view a dielectric is a body capable of resisting and so maintaining this stress, while a conductor is a body incapable of resisting or maintaining the stress, and the electrified surface of a conductor should rather be described as the electrified boundary of the dielectric, and the electrification of the conductor as due to the condition of the dielectric. Professor Maxwell has shown that all electric phenomena can be conceived as due to the condition of the dielectric, or the imponderable medium filling the space occupied by the dielectric. This view is wholly distinct from the old conception that electricity is itself an imponderable fluid.

§ 31. *General Reflections.*—Electricity is not rare, but pervades the world. Our atmosphere is not only electrified, but presents such variety in the intensity and distribution of its electrification that a sense enabling us directly to perceive electricity would frequently disclose a scene as varied as a gorgeous sunset. This sense would reveal the surface of solid bodies delineated by varying electrical density. Dielectrics would be transparent to the new sense, and conductors would be opaque, having their projecting edges, corners, and points marked with startling distinctness. The effect of contact in producing or maintaining difference of

potentials would be perceived by a difference in electric brilliancy, and this difference would vary with each re-arrangement of the objects. Every movement of our body, each touch of our hand, and the very friction of our clothes, would cause a play of effects analogous to those of light and shadow on the eye, while more highly electrified matter would bring into prominence by induction the electrical differences between surrounding bodies. This speculation, however fanciful, helps us to conceive the omnipresence of electricity, and since the mechanical conditions required to excite sensation are fulfilled in the electrical relations between bodies at different potentials there does not seem any very great boldness in suggesting that some living things may have an electrostatic sense so far developed as to be useful to them. Our hair by standing on end would make us when blindfold aware of the presence of any very highly electrified body in our neighbourhood; and an electrometer, acting under the influence of forces similar to those which give us this perception, could be made to indicate the neighbourhood of, say, the wall of a room, in its ordinary electrical condition. It is at least possible that the organs of some animals may be as sensitive as the electrometer, inasmuch as the difference between our own perception and that which they would experience is merely one of degree. Even the whiskers of a cat may be sensitive enough to perceive ordinary electrification. To produce continuous sensation *work* must be done to the sensitive organ, and electric induction can only do *work* upon a body in motion. An electrostatic sense would in this respect be analogous to that of touch. Without eyes we might never have discovered the existence of light, for experiments in optics would in that event have been more difficult to perform than experiments on electricity now are, inasmuch as the mechanical action of light is much feebler than that due to electricity. By direct perception we have become aware of the vast importance of light, and it is probably owing to the absence of direct

perception that we do not yet know the part which electricity plays in the economy of nature. We are learning that electrical phenomena are not isolated, but form one group of the vast series of effects due to an imponderable medium in which, and by which, matter exists; light, electricity, heat, and gravitation, all depend on this medium, and are in some way connected with one another and with massive matter. Much remains to be done to make this connection clear, but the dependence cf electrical phenomena one upon another is well understood, by which words we mean that the conditions of an electrical problem can be set down numerically, that all electrical results can be expressed numerically, and that the connection between data and their consesequences can either actually be calculated or is seen to be calculable.

CHAPTER III.

MAGNETISM.

§ 32. *A Magnet.*—Certain pieces of steel and of the iron ore called loadstone have special properties in virtue of which they are called magnets. A magnet suspended by its centre of gravity, but free to turn in any direction, will only remain at rest when a certain line in the magnet called the *axis* points in a definite direction. The forces which turn the magnet into this direction, or maintain it there, are due to the action of some other body which may be a magnet. The space where a magnet experiences this action is called a *magnetic field.* The earth produces a magnetic field. The forces experienced by a magnet, and due to the earth's magnetic field, are sensibly the same at all parts of any space of moderate extent, such as a room.

Within this space the field is therefore called *uniform.* In a uniform field the *direction* of the magnetic force is the direction which the axis of a freely suspended

magnet would assume. When the axis of a magnet does not coincide with that direction, two equal and opposite parallel forces act on the magnet; these forces tend to turn the magnet so as to bring the axis into the direction of the magnetic force. The body producing the magnetic field experiences equal and opposite forces tending to turn it in the opposite direction. A magnet produces a magnetic field in its neighbourhood, and modifies any magnetic field previously existing there. The field due to a magnet is not uniform; the forces may be much greater than those due to the earth. Magnetic fields are also produced by electricity in motion (§ 45). Under the undisturbed action of the earth's magnetic field, one end of the axis of any magnet points in a direction which differs indeed at almost all parts of the earth's surface, but which may be roughly described as northerly. That end of the axis or magnet is called the north end, which points northward, and the other end is called the south end. The north ends of two magnets repel one another; the south ends repel one another; a north and south end attract one another. The mutual action between two magnets may be described as approximately similar to that which would be produced by four links arranged as in the following diagram (fig. 11). Links on which the arrow-heads converge represent attraction; links on which they diverge, repulsion. The points in the axis at which the imaginary links would abut are called *poles*.

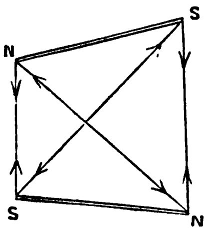

Fig. 11.

If a magnet be broken into any number of pieces, each piece is found to be a magnet. This shows us that the properties of magnets must be due to a polarised condition of each particle of the matter which composes them; by polarised we mean that "each particle possesses properties related to a certain line

or direction in the body, such that when the body retaining these properties is turned so that the direction is reversed, then as regards other bodies these properties of the particle are reversed."*

§ 33. *Poles of Bar Magnets.*—Magnets which are long and thin relatively to their cross section are called bar magnets. Bar magnets act on one another, and are acted on by a magnetic field, almost exactly as if the forces were exerted at or by two simple points in the axis of each. These points are called the north and south poles, and are near the north and south ends of the axis. The forces in action between two bar magnets are therefore very exactly represented by the system of four links shown in fig. 11. The action of magnets which are not strictly bar magnets may usually be represented with some degree of approximation as due to two poles. The force which a hollow magnet exerts on points within it cannot be represented as due to two poles; and in general the less a magnet resembles a bar the less can the forces due to it be conceived as starting from mere points. These forces must then be conceived as distributed forces of unequal intensity and varying direction. What follows in this article must be taken as applying accurately to ideal bar magnets.

The *strength* of a pole is proportional to the force it is capable of exerting on another given pole at a given distance; hence the force f in action between two poles m and m' is proportional to the product $m\,m'$; this force is also inversely proportional to the square of the distance between the poles. The force is not affected by the medium between the poles, except so far as this medium is itself magnetic (§ 36); we cannot, therefore, screen one pole from the action of another otherwise than by surrounding it with a shell of iron. The action of such a shell is too complex to be entered upon in this work. The strengths of the two poles of a bar magnet are always equal. The number measuring the distance between two poles multiplied by the number measuring

* *Matter and Motion.*

their common strength is called the *moment* of the magnet. We will not here consider what units are most appropriate for measuring the strengths of poles, but will simply note that this strength and the moments of a magnet are susceptible of measurement, and that a knowledge of their value gives us full information as to the magnetic properties of any bar magnet.

The forces exerted by bar magnets on one another may result in four different actions: 1st, one magnet may attract the other; 2nd, it may repel the other; 3rd, it may neither attract nor repel the other as a whole, but may tend to turn it round; 4th, it may attract or repel the other, and at the same time tend to turn it round. These four cases present themselves as the relative positions of the poles of the two magnets are changed, and can easily be recognised by thinking of the forces as due to four links like those in fig. 11.

§ 34. *Magnetic Field.*—In a magnetic field (§ 32) a pole is urged in a definite direction with a definite force. The direction in which a north pole is urged is the positive direction of the force of the magnetic field at that point. When the word *direction* of the force of a magnetic field is used without qualification the *positive* direction is usually implied. The *intensity* of a field at a given point is a magnitude proportional to the force which a constant pole would experience there, if by its presence it did not modify the field. The properties of a magnetic field are fully known when the intensity at each point and the direction of the magnetic force are known.

Our conception of the actions which take place in a magnetic field is facilitated by Faraday's geometrical representation of that field as a space traversed by lines which at each point lie in the direction of the magnetic force, and which are so distributed that their frequency is everywhere proportional to the intensity of the field. It has been proved by Clerk Maxwell that if at any part of the course of these lines their number crossing a given area at right angles is proportional to the intensity of

the field, the same proportion between the number of lines per unit of area crossed and the intensity will hold good in every part of the course of the lines. In a uniform magnetic field the lines of force are parallel and equi-distant. Fig. 12 gives a rough representation of the lines of force due to a bar magnet.

§ 35. *Earth's Magnetism.*—The earth's magnetic field is not one which could be produced by a simple bar magnet, nor by any simple or moderately simple system of bar magnets. The earth, therefore, has not got a magnetic pole in the sense given to the pole of a bar magnet. It is usual, however, to call magnetic poles those points on the earth's surface where the direction of the lines of force is vertical. The magnetic pole situated near the *northern* end of the earth's axis resembles what we have called the *south* pole of a bar magnet; the earth's pole in the south resembles the north pole of a bar magnet.

The *magnetic meridian* of a point on the earth's surface is the vertical plane which contains a line passing through that point in the direction of the magnetic force at that point. The direction in which the magnetic meridian lies is shown by the mariner's compass, in which a bar magnet is supported so as to be free to turn in a horizontal plane. The *meridian*, or *true meridian*, of a point on the earth's surface is a vertical plane passing through the point and containing the true axis of the earth; its direction can be ascertained by observation of the stars. The horizontal angle, or angle in azimuth, between the true meridian and the magnetic meridian at a point is called the *magnetic declination* at that point. The vertical angle, or angle in altitude, between a horizontal line in the magnetic meridian and the direction of the magnetic force at a point in that magnetic meridian, is the *magnetic inclination* or dip at that point. The magnetic inclination at a point may be observed by a piece of apparatus called a dip circle, in which a bar magnet placed in the magnetic meridian is supported by its centre of mass

in such a way as to leave it free to move in a vertical plane. In the northern hemisphere the north end of a bar magnet thus suspended points downwards. In the southern hemisphere the south end points downwards. The dip diminishes from the poles to the equator. The line of no dip does not coincide with the equator, and is indeed not constant in position, but varies slightly from day to day and year to year.

The declination varies very greatly and irregularly from place to place. In order to ascertain the true north by means of the mariner's compass we must know the value of the declination at the time and for the point where the observation is made. The value of the declination is given on all charts for the year in which they were issued. The declination and inclination are at every part of the world continually changing. In magnetic storms the changes are rapid, but slight. There are diurnal oscillating variations of declination amounting occasionally to 25′. There are annual oscillating variations of declination which do not exceed 18′, and there are secular oscillating variations, the amount and period of which are not accurately known.

In 1580 the declination in London was 11° 17′ E., that is to say, the north pole of the mariner's compass pointed in a direction more than 11° to the east of the astronomical meridian. In 1657 the declination was zero; the two meridians coincided. In 1800 the declination was 24° 36′ W., and now the declination is still westerly, but less than 20°.

In employing the declination given on charts allowance must be made for the secular variation which has occurred since the chart was issued. The causes of the earth's magnetism, and of the changes of this magnetism, are not yet determined.

§ 36. *Magnetic Induction.*—A piece of iron not of itself a magnet will, if placed in a magnetic field, become magnetised in the direction of the lines of force in the field. Thus a bar of iron placed with its longest axis in the direction of the lines of magnetic

force will become a bar magnet, having its north pole at that end of the axis towards which a north pole would under the influence of the field tend to move. Fig. 12 shows the position of poles in small pieces of wrought-iron placed in a field due to a comparatively large bar magnet.

The action by which iron becomes magnetic in a magnetic field is called *magnetic induction.* In a uniform magnetic field iron magnetised by induction is not impelled in any direction by the magnetic force, which acts with equal and opposite force on the two induced

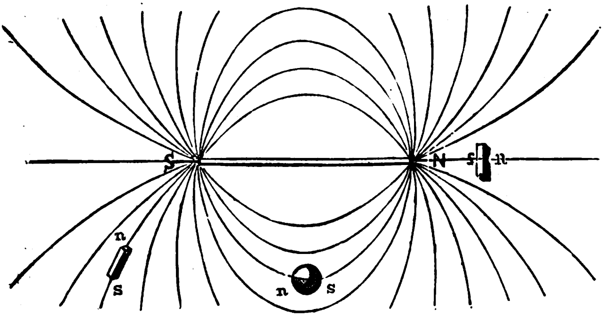

Fig. 12.

poles. When the field is not uniform the induced poles, which are themselves equal, are unequally acted upon, and motion tends to take place in the direction in which that pole would be urged which lies in the stronger part of the field. Thus iron, in virtue of the magnetism induced in it, is attracted by either pole of a bar magnet; for the end of the piece of iron, say near a north pole, will become a south pole, and will be more attracted than the more distant south pole of the iron is repelled. A magnet shaped like a horse-shoe, having poles near the ends, will attract a piece of soft iron placed opposite and across the ends to the

best advantage; for each induced pole will be in the most intense part of the magnetic field which the magnet can produce. A piece of iron placed in this way so as to join the poles of a magnet is called an *armature*. An armature in actual contact with the ends of a horseshoe magnet constitutes the best arrangement for showing strong attraction between iron and a magnet.

Iron in which magnetism has been induced can in its turn induce magnetism in another piece of iron. Thus a magnet may be made to support a long string of nails each in contact with its neighbour, although the further nails may be so remote that the magnetism induced directly by the original magnet would be barely sensible. When *soft* wrought-iron is removed from the magnetic field it loses its magnetism almost completely and with great rapidity. Harder specimens and cast-iron retain more magnetism, and lose what they lose more slowly. Hard steel permanently retains some of the induced magnetism, and loses what it does lose slowly. The power of retaining induced magnetism is described by the somewhat inappropriate term "coercive force."

The name *residual magnetism* is given to that magnetism which either soft or hard iron retains after removal from a magnetic field. Iron in a given magnetic field is more highly magnetised than hard steel, but its residual magnetism is much smaller. It follows from what has been said that one permanent magnet can be used to make an indefinite number of others. To magnetise one bar magnet by another, stroke the new magnet over half its length with the north end of the old one, and over the other half with the south end. Begin the strokes at the centre of the new magnet. A piece of steel will be well magnetised if simply placed like an armature so as to connect the poles of a powerful horse-shoe magnet. The makers of permanent magnets have unpublished processes by which they secure the best results. There is a limit to the intensity with which either iron or steel can be magnetised by any magnetic field, however powerful. When this limit is

not approached the intensity of magnetisation is nearly proportional to the intensity of the field.

§ 37. *Paramagnetism and Diamagnetism.*—Other substances besides iron and steel—notably nickel and cobalt—can be magnetised by induction, acquiring properties similar to those of soft iron, but in a much feebler degree. These substances are all called magnetic or paramagnetic, to distinguish them from other substances, such as bismuth, which also acquire polarity under the influence of a magnetic field, but in which the direction of the induced magnetisation is *opposite* to that of the magnetic force. The latter substances are called diamagnetic. Pieces of a diamagnetic substance placed in the positions of the small pieces of iron in fig. 12 would acquire feeble north and south poles, but the relative positions of these poles would be reversed. One result of these two opposite arrangements of induced poles is that all paramagnetic matter in a magnetic field tends to move from the place of smaller to the place of greater intensity of force, and that all diamagnetic matter tends to move from the place of stronger to the place of weaker intensity of magnetic force. Diamagnetic matter is repelled, paramagnetic matter attracted, by the pole of a magnet; consequently, while a bar of iron, if free to turn, tends under the action of induction to place itself *along* the lines of magnetic force, a bar of diamagnetic matter, such as bismuth, tends to place itself across these lines. All bodies are either paramagnetic or diamagnetic, but the magnetic effects are much feebler with all known materials than with iron or steel.

§ 38. *Ship's Magnetism.*—On board an iron ship the magnetism of the ship itself renders it difficult to ascertain with accuracy by means of the mariner's compass the true direction of the magnetic meridian.

The magnetism of the ship is in part permanent and in part variable.

1st. The permanent magnetism is the residuum of that induced by the earth during the past existence of

the ship, and depends chiefly on the position occupied by the ship while being built. This residuum, although named permanent, undergoes continual modification, to some extent depending on how long the ship's head has been maintained in a given direction, on blows received by the waves, and on other causes. (Blows, it may be here noted, tend to allow molecular adjustments on which probably magnetism depends.)

2nd. The variable magnetism is that induced by the earth at each instant, and varies as four different conditions vary—viz. (*a*) with each change of place; (*b*) with each change in the direction of the ship's head; (*c*) with each change of inclination fore and aft, *i.e.*, by pitching; (*d*) with each change of inclination of the ship as she heels over or rolls.

The Admiralty manual on the deviation of the compass must be referred to for the methods of dealing with effects which the ship's magnetism and its changes have on the mariner's compass.

CHAPTER IV.

ELECTRODYNAMICS.

§ 39. *Preliminary. On Measurement.*—Measurement may be of two kinds: 1st, it may be made by comparison of the magnitude to be measured with another magnitude of the same kind chosen as unit—thus a length is measured by comparison with another length, such as a foot; 2nd, measurement may be made by reference to units of other magnitudes, which magnitudes are in the given circumstance numerically connected with the magnitude to be measured; for instance, a velocity is measured by reference to the units of length and time. In this second kind of measurement the unit employed, such as the unit velocity, may be called a *derived* unit. In § 4 it was shown that a quantity of electricity was a magnitude which could be measured by reference to the units of force and distance.

When the unit quantity has once been chosen, either arbitrarily or by derivation, the number expressing any other quantity may be conceived as simply expressing the result of a comparison with the unit. Any magnitude which can be arithmetically represented by a number may in algebraic formulæ be represented by a letter, and the letter q will hereafter be employed to designate any given quantity of electricity measured in any unit. Similarly we have seen (§ 6) that a difference of potentials is a magnitude which can be measured either in derived or in arbitrary units. The letter i will be employed to designate a difference of potentials expressed in any unit. The letter s will be used to designate a given capacity. The unit capacity is fixed when those of quantity and difference of potential have been chosen, for the system or jar of unit capacity must contain the unit quantity when the unit difference of potentials is maintained between the two conductors.

§ 40. *Current.*—The word *current* is used to denote a continuous flow of electricity. The magnitude or *strength* of a current is, in the most consistent systems of measurement, expressed by a number *equal* to the quantity of electricity passing in a given time, such as a second. The unit current in such a system is a derived unit, viz., that current which conveys the unit quantity per second. In all systems of measurement the numbers employed to represent currents must be *proportional* to the quantities which those currents convey in a given time. The letter c will be employed to denote the strength of a current measured in any unit.

Constancy, uniformity, and equality are terms the meanings of which when applied to currents are obvious when considered in the light of the above definitions.

A constant current along a given conductor is completely described when its direction and numerical magnitude are given. This warning is necessary, because in many of the older books on electricity currents are spoken of as intensity and quantity currents, as if a current might have other qualities than that of

magnitude, position, and duration, which is not the case. Currents may traverse long or short conductors, of various materials and various dimensions, but in all cases the numbers measuring the currents will be equal, if equal quantities pass through these conductors in equal times. The properties of currents are conveniently studied by observations made on metal wires through which constant currents are maintained.

§ 41. *Electromotive Force.*—The name electromotive force, often written for brevity as E.M.F., is given to the property in virtue of which any combination or system tends to produce a current. Thus, when two conductors at different potentials are joined by a wire, a current flows through the wire, and the electromotive force is in this case identical with what we have hitherto called difference of potentials; we shall find presently (§ 50) certain cases in which a current may be maintained in a wire although all parts are at one potential, just as a current of water might be maintained in a horizontal pipe immersed in still water and open at both ends if a wire were drawn through it. The term electromotive force describes the property in virtue of which the arrangements both in the first and second case produce a current of electricity; E.M.F., it will be seen, is not a force at all, but is a magnitude of the same class as difference of potentials. A given E.M.F. is completely described when besides its magnitude we have stated the places between which it tends to cause a current to flow. It is measured in the same units as difference of potential, and will be designated by the same letter, i; in many cases the words difference of potential and E.M.F. may be indifferently employed, but E.M.F. as the cause of a current has a wider signification. E.M.F. cannot exist independently of a source of energy, that is to say, when E.M.F. produces a current, work is done, and the work is necessarily proportional to the product, $i\,q$, as the work done by falling water is proportional to the product of the quantity of water multiplied by the height through which it falls.

§ 42. *Resistance.*—Let i be a constant E.M.F. tending to produce a current in a given constant conductor; for instance, let i be a given difference of potentials permanently maintained between the two ends of a wire. Let c be the current produced in the conductor by i; the quotient $\frac{i}{c}$ is found by experiment to be constant for all values of i and c.

The property in virtue of which each conductor determines a special constant value of the quotient $\frac{i}{c}$ is called the electrical resistance of the conductor. The magnitude of the resistance is measured by a number either equal to $\frac{i}{c}$ or proportional to it.*

Calling r the number measuring the resistance of the conductor, and choosing as unit of resistance the resistance of that wire, or other conductor, for which $\frac{i}{c}$ is one unit, we can write $r=\frac{i}{c}$.

This equation is commonly known as Ohm's law. Experimentally it is found that a conductor of uniform material and constant cross section, such as a wire, has a resistance proportional to its length; also that the resistance of a conductor of uniform material and cross section is inversely proportional to that cross section. The resistances of similar conductors made of different materials differ greatly. The *specific resistance* of a material is the resistance of some definite volume or mass of the material definitely placed relatively to the E.M.F. acting on it, as, for instance, the resistance between two opposed faces of a cubic foot of the material, or the resistance between the ends of a wire of the material a foot long and weighing a grain. The specific resistance of metals increases, but that of insulators decreases as

* Graduated lengths of wire representing each a definite number of units of resistance are sold by opticians under the name of resistance coils.

their temperature rises. Copper and silver have a low specific resistance relatively to iron, and iron relatively to German silver. The *conductivity* of a wire or other conductor is the reciprocal of its resistance or $\frac{1}{r}$. The specific conductivity of a material is the reciprocal of its specific resistance.*

§ 43. *Varying Currents.*—A constant E.M.F. maintains a constant current in a conductor of constant resistance; but this permanent state is not reached at the very instant in which the E.M.F. begins to act. Thus if a current is produced in a wire by suddenly and permanently raising the potential at one end while the potential at the other is kept constant by being joined, for instance, with the earth, the current will begin at the end remote from the earth, and will gradually extend to the other end, changing by degrees at each section of the wire from zero to its final permanent condition. The flow of electricity in this case is analogous to the flow of heat along a rod of metal when one end is suddenly and permanently brought in contact with a constant source of heat, while the other end remains cool. The analogy would be perfect if we could prevent any leakage of heat by conduction or radiation from the exposed surface of the conducting rod. The change, which with heat is slow, occurs so rapidly with electricity as to appear instantaneous to the unaided senses. We shall not in this work study the condition of the current while changing.

A constant current is necessarily uniform at all cross sections of any single conductor along which it flows; that is to say, equal quantities pass each section in equal times.

§ 44. *Force exerted by one Current on another.*—Parallel wires in which two currents are flowing in the

* Incident light affects the resistance of some if not of all materials. Light falling on crystalline selenium diminishes its resistance. *Vide* Willoughby Smith's paper, *Journal of the Society of Telegraph Engineers* for 1877.

same direction attract one another; parallel wires in which two currents flow in opposite directions repel one another. This is usually and conveniently expressed by saying that the currents themselves attract or repel one another, and this mode of expression will hereafter be used. The repulsion or attraction of any currents in any wires, however disposed, may be deduced from the following laws laid down by Ampère as giving results in strict accordance with his experiments.

1. Let short lengths l and l', which we will call elements of the currents c and c', be parallel to one another and placed (fig. 13) so as to be perpendicular to the direction of the line d_1, measuring the distance between them. The force between these elements is in the direction of the line d_1; it is an attraction if the currents are flowing in the same direction, a repulsion if they are flowing in opposite directions, and it is proportional to the expression $\frac{l\,l'\,c\,c'}{d_2}$.

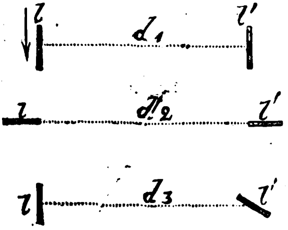

Fig. 13.

2. Let the elements l and l' be placed so as to lie in the direction of the line d_2, the force will be half as great as when the elements are placed as in case 1, and will act in the same directions as in case 1.

3. Let the elements l and l' be placed so that while both are perpendicular to the line d_3, their directions are also perpendicular to one another; the force between them will be nil.

The effect of any element of a current is equal to the resultant effect from three elements of the same strength at the same spot running at right angles to one another, and having such lengths and directions that the original

element forms the diagonal of a rectangular parallelopipedon of which these substituted currents are the sides.

These laws enable us, from the force experimentally determined for case 1, to calculate the force between any pairs of elements however placed. To do this we substitute for each original element three others which relatively to one another and the line *d* occupy the three positions shown in fig. 18; then, laws 1, 2, and 3 give us the forces which each substituted element exerts on the others. In consequence of law 3 the effective forces between the six elements are reduced to three, and the resultant of these three forces is the force between the original elements.

Further, these laws, by enabling us to calculate the effect of each elementary part of any current on all other parts of another current, enable us by mere summation to calculate the total force which a permanent current in any fixed wire will exert on another permanent current in any other fixed wire. The difficulty of doing this is purely mathematical; the sufficiency of the principles involved may be perceived by those who are unable to apply these principles even to the simplest cases.

It follows from the above laws that two currents in wires which are not parallel attract one another, if both currents flow to or from the apex of the acute angle which the direction of the wires make with one another. The currents repel one another if one approaches and the other recedes from the apex of the acute angle between them.

§ 45. *Force between Currents and Magnets.*—A current passing through a long straight wire exerts a force on the pole of a magnet tending to make that pole travel round the axis of the wire. The direction of the force is perpendicular to the plane passing through the pole and the axis of the wire. In other words, a straight current produces a magnetic field in which the lines of force (§ 34) are circles concentric with the wire. The force is proportional to the strength of the pole and to

the strength of the current. When the current is conveyed by a *long* straight conductor the force is inversely proportional to the distance between the pole and that conductor. A north pole will be urged in the same direction as the hands of a watch are seen to move when held facing a person who looks along the conductor in the direction of the current; a south pole will be urged in the opposite direction. It follows that the two poles of a magnet in the neighbourhood of a straight wire are acted upon by opposite forces, which tend to place the magnet at right angles to the direction of the current.

If a wire be bent into a curve each element will act on the pole of a magnet in the same manner as a short current flowing in a straight wire tangent to the curve at that point. A short straight current acts on the pole of a magnet in the same direction as a long straight current, but the magnitude of the force is inversely proportional to the *square* of the distance between the element and the pole. It follows that when a wire is bent into a circle a current flowing round the circumference acts on a pole at the centre with a force proportional to the strength of the current and to the strength of the pole, and inversely proportional to the radius of the circle. If the wire be bent many times round the circumference of the circle each turn produces an equal effect, so that the force is directly proportional to the number of turns in the coil.

The magnetic field caused by a coil tends to set a magnet at right angles to the plane of the coil, whether this be circular or not. The magnetic field due to a circular coil is strongest at its centre. If the centre of mass of a bar magnet be in the plane of the coil the forces acting on the two poles will be equal as well as opposite, and will not tend to move the magnet as a whole, but only to make it point in a definite direction. If, however, the magnet be at one side of the coil and pointing in the direction determined by the field, the magnet will experience forces tending on the whole to bring its centre towards the plane of the coil.

A current flowing round any plane closed curve produces a magnetic field similar to that which would be produced by a sheet of iron enclosed and bounded by the curve and magnetised transversely; *i.e.*, so that its polarisation is perpendicular to the plane of the curve. If we go to that side of the closed curve from which the current will be seen to circulate in the direction of the hands of a watch held parallel to the plane of the curve with its face towards us, the northern face of the sheet of iron will be the further from us.

The name solenoid is commonly given to a helix of wire such as is shown in fig. 14, so arranged that a current

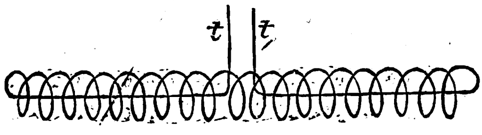

Fig. 14.

can enter by the terminal t and flow continuously round the helix, leaving again by the terminal t'. A solenoid traversed by a current produces a magnetic field which, *outside* itself, is similar to that produced by a bar magnet of the same length and having its axis coincident with that of the solenoid. It will therefore behave as a magnet with poles. Imagine a watch so placed in the solenoid that the hands move in the same direction as the current circulates; the face of the watch will then be turned towards the end which acts as a south pole.

The force exerted on a current by a magnet is obviously equal and opposite to that exerted on the magnet by a current. Hence every element or short length of a conductor conveying a current at right angles to the lines of force due to the magnet is acted upon by a force perpendicular to the plane passing through its own direction and the lines of magnetic force. This force is proportional to the length of the

element of the conductor, to the strength of the current, and to the intensity of the field.

Let O M (fig. 15) be the direction of the lines of magnetic force. Let the plane O A M be that in which the element lies; this element, when conveying a current in the direction shown by the arrow, will experience a force perpendicular to the plane A O M. The direction of this force is indicated by the arrow O F, and is that in which a right-handed screw, the axis of which is at right angles to the plane A O M, would advance if turned, as indicated by the curved arrow, from the direction of the current to that of the magnetic force.

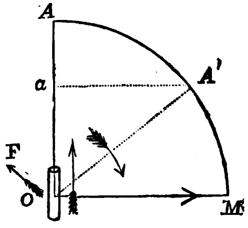

Fig. 15.

When the element conveying the current is not at right angles to the direction of the lines of magnetic force the direction of the force remains as stated relatively to the plane A O M, but its magnitude diminishes according to the following law.

In the plane O A′ M draw the line O A perpendicular to O M, and of a length representing in magnitude (though not in direction) the force which the element experiences when lying in the direction O A. If now the element be inclined towards O M, so as to lie in the direction O A^1, the force on the element will continue to act in the direction O F, but will be diminished in the ratio of O A : O a. This is briefly expressed by saying that the force is proportional to the sine of the angle M O A′. The force vanishes when the element lies in the direction O M of the lines of force. The phenomena demonstrating the existence of a force between currents and magnets were first observed by Oersted.

§ 46. *Magnetism induced by a Current.*—Since an electric current produces a magnetic field, iron introduced into this field will be magnetised in the direction of the lines of force. An intense field is produced inside

a coil when the turns are numerous and the current strong. A soft iron wire or rod placed inside such a coil or solenoid is strongly magnetised, and is called an *electro-magnet*. The polarity of the wire or rod will be reversed when the direction of the current is reversed, and the wire or rod will lose its magnetism when the current ceases. The north pole of an electro-magnet will be at the north end of the solenoid (§ 45). The introduction of soft iron inside a coil or solenoid does not produce magnetism (§ 34), but diminishes very much the force in the space occupied by the iron and augments it in the outside end spaces. The action of the soft iron might be compared with that of a lens which rarefies light at one place to make it correspondingly more intense at another.

§ 47. *Electrical Circuits.*—The name circuit is given to conductors forming an endless band round which a current can flow; as when a wire is bent round and its two ends joined. A circuit may be of any form, and may consist of any number of different materials, such as wires, earth, or water, provided these are so joined that a particle of electricity starting at any point, and moving continually forward, would come back to that point as often as it went round the circuit. When an insulator separates two parts of a conductor or conductors which when joined form a circuit, the circuit is said to be broken (or open). When the insulator is removed, as, for instance, when the two ends of a wire which have been separated by air are brought together, the circuit is said to be completed (or closed). A current may flow from one body to another through a conductor which does not form part of a circuit, but in the majority of cases which we shall have to consider currents flow round complete circuits, and are of equal strength at all parts of the circuit. The earth often forms part of a circuit, as when the two ends of a long telegraphic wire are connected with moist earth or water.

§ 48. *Frictional Machines give Feeble Currents.*—No practical means has so far been indicated by which a current could be permanently maintained. To do this

we must have a means of producing and maintaining electromotive force in a conducting circuit.

In frictional machines great electromotive force is produced, but it is an essential part of the contrivance that the rubber and collecting points shall be separated by the insulator which is rubbed. We cannot, therefore, even if we join the rubber with the main conductor, complete a circuit of conductors. If we look on the insulator as a conductor having a very high resistance we find that the circuit formed when the rubber and main conductor are joined has such an enormous resistance that, according to Ohm's law (§ 42), even the great E.M.F. produced by the machine can only produce a very feeble current.

§ 49. *Magneto-electric Induction.*—The action of a magnetic field on a conductor moving in it gives a practical means of producing and maintaining strong currents. A conductor when not conveying a current, and when at *rest* in a constant magnetic field, experiences no other force due to the field than simple magnetic or diamagnetic action. This force is practically insensible, except when the conductor happens to be iron; but when any conductor whatsoever is moved in a magnetic field a new effect is produced. Every part of the conductor while being moved *across* the lines of magnetic force experiences an E.M.F., tending to produce a current through the conductor so directed that the mechanical force due to the interaction between the magnetic field and the current tends to resist the motion of the conductor. The action producing this E.M.F. is called *magneto-electric induction*,* and the law just stated is called Lenz's law.

Case 1. Let us consider an element or short length of a conductor, such as a wire A B (fig. 16); let this element be placed so as to be perpendicular to the lines of magnetic force A M in the field; so placed, therefore, that any current in it will experience the maximum

* There is no essential difference between magneto-electric and electro-magnetic.

possible force due to that field; let this element be moved in a direction, A D, perpendicular to the plane determined by its own direction and that of the lines of force in the magnetic field.* An E.M.F. will be produced in the element tending to produce a current from A to B, that is to say, a current which (§ 45) would resist the motion of the element. The E.M.F. produced on each element of an actual wire placed in a magnetic field, and moving across it in the manner described, will be proportional to the length of the element, to the velocity of its motion, and to the intensity of the part of the field traversed. This intensity (§ 34) may be represented by the *frequency* with which lines of force occur, so that the above statement is equivalent to saying that the E.M.F. produced by moving a wire in the manner described in a magnetic field is proportional to the number of lines of force which the wire cuts across in a given time. The wire in case 1 is moving in a direction, A D, directly opposite to that in which the force due to the magnetic field acts on the current.

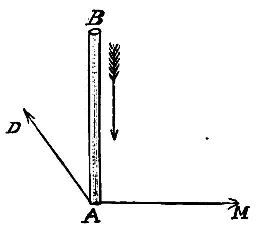

Fig. 16.

Case 2. If the wire were moved in either direction at right angles to this, *i.e.*, along A M or A B, or in any manner whatsoever in the plane B A M, no E.M.F. would be produced along the wire. We already know (§ 45) that if a current were produced by any cause in the wire A B the force due to the magnetic field on the current would not tend to impede its motion in the plane B A M. The wire, by motion in this plane, would cut *across* no lines of magnetic force.

Case 3. If the wire were lying along the direction A M, we know (§ 45) that a current in it would experience no force due to the magnetic field. No electro-

* The point D is supposed to be behind the paper.

motive force is therefore produced in an element lying in the direction of the lines of magnetic force. If moved in any direction by a motion of translation it would, during this motion, cut *across* no lines of magnetic force.

Case 4. Let us lastly consider the general case of an element placed in any direction relatively to the lines of magnetic force, and moved in any direction with a motion of translation. The E.M.F. will be simply proportional to the number of lines of force cut across by the element in a given time. The three cases have been considered separately in order that there might be no misapprehension as to the meaning of the words "cut across." The proof of the general proposition is easily deduced from the three elementary cases, with two additional assumptions verified by experiment. *a.* The wire A C behaves as to E.M.F. as if composed of the bent wire A B C (fig. 17), where B C is parallel to A M, the direction of the magnetic force, and A B is perpendicular to B C. Then during any motion of translation we may, so far as E.M.F. is concerned, neglect the part B C (*vide* case 3).

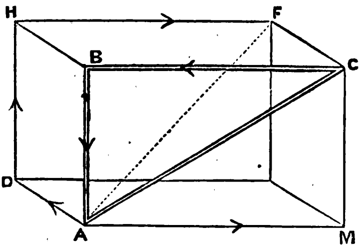

Fig. 17.

b. The E.M.F. produced by the simultaneous motions A D, D H, and H F is the same as that produced by the single motion represented by the line A F. The motion described in the two ways is merely one and the same motion. By case 2 the motion along D H and that along H F can produce no E.M.F. The wire B C, by case 3, produces no E.M.F., whatever be its motion. There remains as the efficient cause of E.M.F. the motion of A B along A D; but the wire A B moving along A D is an example of the first case, and the E.M.F. in this case is

known to be proportional to the number of lines cut across in a given time; but the original wire A C in moving along the line A F will cut across the same number of lines, therefore the E.M.F. produced in any element, A C, moved in any way, will be proportional to the number of lines cut across in a given time, which was to be proved.

§ 50. *Electromotive Force due to Magneto-electric Induction in a Circuit.*—The whole electromotive force acting on a circuit is the sum of the electromotive forces acting on its different parts, and tending to produce a current in one or other direction round the circuit.

When all the elements in which electromotive force is induced lie in one plane, the calculation of the resultant E.M.F. is comparatively simple.

Let us consider, first, a circuit consisting of a moveable wire A B (fig. 18) sliding on a fixed wire C D E; let A B and C D E lie in one plane, so placed in a magnetic field that when the wire A B slides along C D E it moves across lines of magnetic force, the direction of which is shown by the line S N. It follows, from the principle stated in the last paragraph, that when A B moves in the direction of the arrow an E.M.F. will be produced in the circuit proportional at each instant to the rate at which the number of magnetic lines of force passing through the area A D B is being increased. If the motion of A B be reversed, the direction of the E.M.F. will be reversed, and its magnitude will at each instant be proportional to the rate at which the

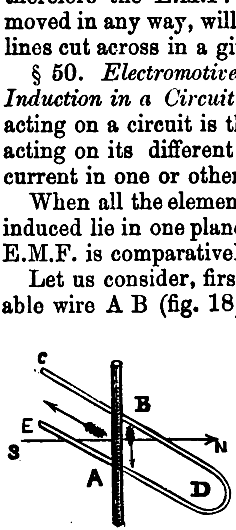

Fig. 18.

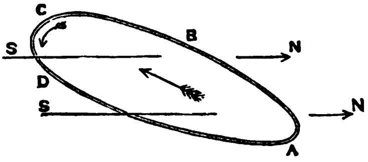

Fig. 19.

number of lines of force passing through the area A B is being diminished. In both cases the *rate of change* of the number of lines of force included within the area is proportional to the E.M.F. induced. Let us next consider a plane circuit of one wire A B C D. Let this move with a motion of translation, as shown by the arrow, across lines of magnetic force. At one point on each side, near B and D, where elements of wire move, as in case 2, § 49, there will be no E.M.F. In front and behind these points each element of the wire will experience an E.M.F., which will be greatest near C and A. The E.M.F. in the front and back portions will be in the same direction relatively to external bodies, but in opposite directions round the circuit. The E.M.F. due to all the elements of the front portion will exactly balance the E.M.F. due to all the elements of the back portion, if on the whole there is no change in the number of lines of force piercing the area A B C D. If this number increases, the E.M.F. will be in the direction of the arrow near C; if it diminishes, the E.M.F. will be in the opposite direction. The magnitude of the E.M.F. will, as in the first case, be proportional to the rate of change in the number of lines piercing A B C D. Again, let the circuit be placed as in fig. 20, and let it spin round an axis O P perpendicular to the direction of the lines of force. At the moment when the circuit is in the position shown in a plane perpendicular to the lines of force there will (case 2, § 49) be no E.M.F. in any part of the circuit; but as soon as the circuit leaves this plane the motion of each element, instead of being parallel to the direction S N, becomes oblique to it, and if the rotation be right-handed, looked on from

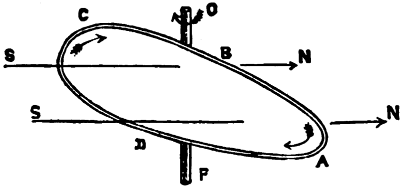

Fig. 20.

above (case 4, § 49), an E.M.F. will be induced in the direction shown by the arrows in all the elements of the ring or circuit.

In a uniform field this E.M.F. will be a maximum near A and C, and will diminish as B and O are approached, where at one point it will be zero. If the motion of rotation be uniform, the E.M.F. will increase as the plane approaches the position perpendicular to that drawn, at which every element in the circuit will move in a direction at right angles to the lines of force; during the next quarter of turn the E.M.F. will decrease until A has reached the position occupied by C in the drawing, when it will be again zero. During the next half revolution the E.M.F. will be in the opposite direction round the ring, *i.e.*, from D to A B C, but the direction of the E.M.F. and current will be the same relatively to exterior bodies as during the first half revolution. The E.M.F. is at each instant proportional to the rate of change in the number of lines passing through the area of the circuit. From a consideration of § 49, it may be seen that this law is necessarily general whatsoever be the kind of motion of the plane circuit. We may then increase the E.M.F. obtained by magneto-electric induction by increasing the intensity of the field, or by increasing the velocity of motion suitably directed in the field. If a wire be made into a coil, each turn of the coil experiences an independent E.M.F. Thus a coil of 100 turns, spinning like the ring of fig. 20, will experience a hundredfold the E.M.F. induced in the simple ring spinning with the same velocity in the same field. Thus by simply spinning a coil in a magnetic field we can produce a current which is reversed in the circuit at each half revolution. The arrangement will be most efficient when, as in fig. 20, the axis of the coil is at right angles

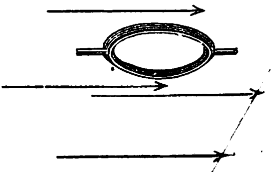

Fig. 21.

to the lines of force. If the axis of the coil is placed, as in fig. 21, parallel to the lines of force, no current will be induced. In this case no lines of force traverse the circuit in any position; the E.M.F. produced in each upper element as this moves across the lines of force is necessarily counterbalanced by an opposite and equal E.M.F. in an element of the lower part of the circuit simultaneously cutting the same lines. This fact enables us to ascertain experimentally the direction of the lines of magnetic force in any uniform field, such as that of the earth, at any place with more accuracy than could be done by direct experiments on pivoted magnets, in using which the effects of gravitation and of friction often overpower the effect of magnetism.

§ 51. *Galvanometer.*—The galvanometer is an instrument by which the presence of a current in a circuit may be observed, and by which the relative strengths of currents may be compared. The simplest form which is practically useful is the reflecting galvanometer as made by Sir Wm. Thomson. This instrument may be constructed without the help of an optician. Wind copper wire insulated with silk (or even cotton) on a hollow cylindrical bobbin A, with deep flanges, fig. 22. The bobbin may be all of brass, or the centre core may be a brass tube and the flanges of wood. Support the bobbin by means of the flanges in any convenient way. Inside A fit a small brass plug D, having at one end a hollow chamber closed by the lens E, with a focal distance of about 30 in.; in the little chamber suspend a magnet

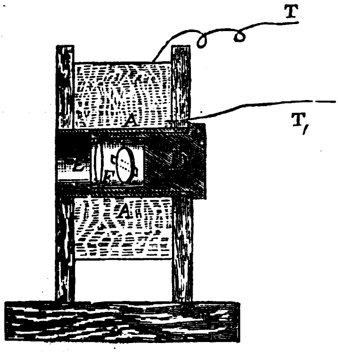

Fig. 22.

with a very light mirror cemented to it. The fibre used for the suspension should be so thin as to float upwards when held by one end; fibres such as this can easily be pulled out of cheap silk ribbons; a piece of warmed shellac drawn quickly across the end of the fibre will form on it a little shellac needle, by which the fibre can then be easily handled. The fibre must be fixed to the hole in the plug from which it hangs and to the magnet by cobbler's wax, or some such cement, which will not run along the fibre and clog it. The mirror should be of microscope glass, as truly plane and as light as possible. Suitable mirrors, with magnets attached, can be obtained from any London electrical instrument maker, or from Mr. James White, optician, Glasgow. The diameter inside the plug may be about $\frac{5}{8}$ in. The plug is simply pushed into the tube A, and can be withdrawn at pleasure. The wire used to form the coil may be of any dimensions, from, say, No. 40, in which case many thousand turns will be held by the bobbin, to No. 16, in which case the bobbin will hold only two or three dozen turns. Thick wire is most suitable for some experiments, and thin wire for others. In any case the ends T T′ of the wire should be stout, and may conveniently be permanently attached to fixed insulated brass pieces, called terminals, to which other wires can be attached by screws without disturbing the coil wires. The instrument is completed by a paraffin lamp (fig. 23)

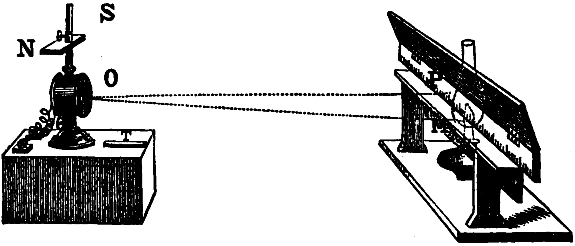

Fig. 23.

placed behind a screen, having on it a scale P as shown, and a slit M, through which the light falls from the lamp on to the mirror.

The lamp and scale are placed at such a height and at such a distance (say 15 in.) from the mirror that a clear, well-defined image of the slit falls on the scale. The mirror will lie north and south, the line M O will therefore lie east and west. It is obvious that if the slit is placed so that the light falls on the mirror in a plane perpendicular to its surface the reflected image will appear straight above the slit at the centre of the scale. A very small angular deflection of the magnet and mirror will be indicated by a considerable deviation of the image along the scale to right or left. The whole arrangement is one adapted to allow a magnet to oscillate with great freedom, and to enable an observer to detect the very small changes in the direction assumed by the mirror. If a current of electricity circulates round the coil it will (§ 45) cause the magnet to deflect from the magnetic meridian to right or left, according to the direction of the current. The bar magnet N S, shown above the coil, enables the observer to modify the directive force of the earth's magnetism so as to make the instrument more or less sensitive. The magnet T is used, by its greater or less proximity, to bring the spot of light to the zero of the scale without sensibly changing the sensibility of the instrument.

N S should lie in the magnetic meridian ; T in a plane perpendicular to the magnetic meridian, and must be reversed, end for end, as it becomes necessary to move the spot of light to the right or to the left.

§ 52. *Experimental Illustration of Magneto-electric Induction.*—Fix the plug, magnet, and mirror of the galvanometer described in the last paragraph firmly on an upright cylindrical support B (fig. 24) ; place the lamp and scale as for the galvanometer. Arrange a stout copper ring D so that it can be made to spin round a vertical axis so as not to shake the plug. Then if the ring be made to spin, the image on the scale will be

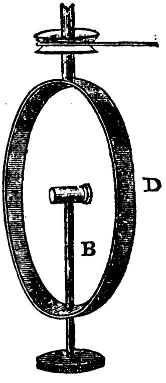

Fig. 24.

seen to deviate from its position of rest or zero. If the speed of the revolutions be increased the deviation will increase in the same ratio. If the direction of motion be reversed the direction of the deviation will be reversed. The deviation indicates the current induced (§ 50) in the ring by the earth's magnetic field. The current producing the deviation is intermittent, but the succession of impulses given by the succession of currents follow one another so rapidly that the inertia of the magnet and mirror keep them sensibly still when the speed of rotation of the coil is uniform. The deviation of the spot of light indicates the average effect of the varying current.

If the spinning ring be changed for one of the same metal with smaller or larger cross section, the deviation of the spot of light on the scale, *i.e.*, the average current will, for equal speeds, be proportional to the cross section employed. This illustrates Ohm's law, for the E.M.F. will be the same in all cases, and the resistance will be inversely proportional to the cross section of the ring; the current, therefore, will be directly proportional to the cross section. If we replace a simple ring by a coil of silk-covered wire of the same section as that used for the ring, the current due to a given speed will be the same as in a single ring. The E.M.F. is increased in direct proportion to the number of turns, but the resistance is increased in the same proportion, and therefore the current remains constant; but the deviation of the spot of light will be proportional to the number of turns of the wire, for each turn acts on the magnet independently of all the others. We obtain the same deflection with the same quantity of metal in the ring, whether arranged as a thick rod or as

a coil of fine insulated wire; but in the one case this deviation is due to a strong current going once round, in the other case to a weak current going many times round. The direction of the deflection of the magnet will be that in which the coil is turned. In experiments intended to verify the above laws with accuracy, many precautions are necessary, and the strict connection between the result of experiment and the principles laid down can only be shown by very complex mathematical expressions, but approximate results illustrating the above laws are easily obtained.

§ 53. *Induced Current observed by Galvanometer.*—*a.* Let the plug be replaced in the galvanometer, and let two wires be led from the terminals of the galvanometer to press against two insulated brass semicircular sliding pieces attached to and rotating along with the rotating coil described in the last experiment. Let the ends of the rotating coil be each connected with one of these sliding pieces. We shall then have a circuit comprising the rotating coil and the galvanometer coil. This circuit will be broken twice during each revolution, and when reclosed each end of the galvanometer will alternately be in connection with each end of the rotating coil. The break should be so placed as to correspond, roughly at least, with the position in which the smallest E.M.F. is experienced by the coil. If the coil be now made to spin, a rapid succession of intermittent currents will be induced, which will pass in the same direction round the galvanometer coil, and cause a sensibly constant deflection. The length and thickness of the wire in the galvanometer should not be very different from that in the rotating coil. The magnitude of the current observed will be sensibly proportional to the velocity of rotation of the coil. If a length of insulated wire be introduced into the circuit between the rotating coil and the galvanometer terminal, the current will be reduced in proportion as the resistance of the whole circuit is augmented. If the rotating coil be changed for one with a greater number of turns of the same

sized wire the current, corresponding to any given speed of rotation, will be increased; inasmuch as the E.M.F. will be increased in proportion to the number of turns in the rotating coil, while the resistance of the whole circuit will be increased in a less ratio, since that part of this resistance which is due to the galvanometer remains constant. Many other experiments illustrating Ohm's law can be made with this apparatus.

b. Let the ends of a long hollow coil of silk-covered copper wire be attached to the terminals of a galvanometer, and placed at such a distance from the instrument that a bar magnet about to be used shall not directly affect the galvanometer. If then the bar magnet be suddenly introduced into the hollow coil, a sudden current will be induced in the coil and indicated by the galvanometer. The spot of light will be jerked to one side, but if the magnet be left at rest inside the coil, the induced current will cease, and the spot of light come back to its central position. If then the bar magnet be suddenly withdrawn, an equal transient current will be induced in the opposite direction. The student can apply Ohm's law and the principle of § 50 to discover the effect produced by varying the wires in the coil and galvanometer, and also by varying the dimensions of the parts. It is clear that introducing a magnet inside a coil causes a large number of lines of magnetic force to traverse the area embraced by the circuit.

c. For the same reason, if a rod of soft iron be placed inside the long hollow coil just described and then magnetised in any way, a current will be induced in the coil. When the soft iron rod is demagnetised a current will be induced in an opposite direction. In the above experiments analogous effects will be produced if the magnet or iron be not actually inside the coil, but be brought near one end. Indeed there are few cases in which it is possible to move a magnet near a circuit without inducing a current, or to move any part of a circuit on the earth's surface without inducing a current; but the induced currents are often too feeble to

be observed with ease. The examples described have been chosen among those in which comparatively powerful effects are produced.

§ 54. *Electro-magnetic Induction, or Induction due to Currents.*—A current produces a magnetic field, § 45. If, therefore, any circuit or part of a circuit be moved in the neighbourhood of a current, each element of the circuit will be subjected to an E.M.F. which may be calculated by the principles of § 49. In general, therefore, the relative movement of two conductors, each of which forms part of a circuit and one of which conveys a current, will have the effect of inducing a current in the other. The inducing current and conductor are called *primary*, the induced current and the conductor in which it flows are called *secondary*. The effect to be expected in particular cases may be deduced from the principles laid drawn in § 45 and § 49—each element of a straight primary current when moving towards a straight parallel secondary conductor produces an E.M.F. in each element of this secondary conductor, acting in a direction opposed to that of the primary current.

Two coils of insulated wire wound so as to form flat spirals may be conveniently employed to show the inductive action of currents. Let them be placed as in fig. 25, parallel to one another, and perpendicular to a common axis. Let a primary current due to some independent E.M.F, at I circulate in the coil A. Then

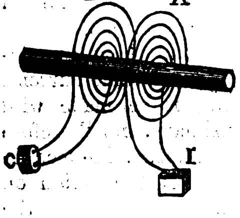

Fig. 25.

the approach of the two coils along the axis will cause a secondary current in the coil B opposed in direction to that in A. This current may be observed in a galvanometer at C; the secondary current in B will be in the same direction as the primary in A when the coils are moved apart along the axis. Each element of the primary current in this apparatus acts on all the neigh-

bouring elements of the secondary coil to produce an E.M.F. in the same direction.

The increase or decrease of a current in a primary wire increases or decreases the number of lines of magnetic force passing through secondary circuits in the neighbourhood, and will therefore induce currents in these circuits. The commencement or cessation of a current by causing a very rapid change of intensity in the magnetic field containing a secondary circuit exerts a very powerful inductive action. Thus, let a long hollow secondary coil of insulated wire be placed outside a similar long primary coil, the commencement of a current in the primary will induce a current in the opposite direction through the secondary; its cessation will induce a current in the same direction as the primary current. When the current in the primary wire has attained its permanent state, neither increasing nor decreasing, the induced current will have ceased; a rapid succession of currents of short duration sent in one direction through the primary coil will induce the same number of currents in each direction through the secondary wire, so that the total number of the induced currents will be double that of the primary currents. The effect is much increased by filling the space inside the primary coil with soft iron which is alternately magnetised and demagnetised by the primary wire; we then have a double effect on the secondary wire—one due to the direct action of the primary, and one due to its indirect action, through the iron. The contrivance known as a Ruhmkoff's coil acts in the way described.

If the primary wire is made stout and thick a moderate E.M.F. will produce in it a considerable current. If the secondary wire surrounding it be made with very numerous turns close to the primary, and therefore of a long and thin wire, the total E.M.F. induced in the secondary wire due to the sum of the action on all the turns may be made very much greater than the E.M.F. producing the primary current. This will not produce a stronger current than flows through the

primary coil, but it will enable effects to be produced which the original source of E.M.F. could not produce. Thus, if the secondary circuit be broken, considerable sparks similar to those produced by frictional machines may, when the primary current begins and ends, be observed to fly across the air between the ends of the secondary circuit held opposite one another for the purpose of the experiment. Long sparks may be obtained from the secondary circuit when the E.M.F. acting in the primary circuit is insufficient to cause any visible spark.

When instead of wires we consider two conductors of any other given shape, in one of which a current is flowing, the problem of the inductive action due to their relative motion becomes extremely complex. We may, however, see that any change which occurs in the magnetic field, in which a conductor of any shape whatsoever is placed, will by electro-magnetic induction cause currents throughout its mass.

An induced current, in accordance with Lenz's law (§ 49), always flows in such a direction that the force between the primary and secondary coils tends to oppose a motion inducing the current. If due to an increase of magnetism in a magnet, or to an increase of the current, the induced current tends to retard that increase; if due to a decrease of magnetism or current, it tends to retard that decrease. It follows that the motion of a conductor conveying a current, or of a magnet, is invariably opposed by induced currents in all neighbouring conductors. This action is illustrated by the fact that a magnet swinging over a conducting (non-magnetic) plate comes to rest much sooner than if the plate be removed. The fundamental facts of electro-magnetic or magneto-electric induction were discovered by Faraday.

§ 55. *Magneto-electric Machine.*—The name magneto-electric machine is given to any apparatus in which permanent magnets are used to induce a continuous succession of induced currents. Wilde's, Siemens',

and Ladd's machines will produce currents of sufficient strength (§ 72) to fuse by their passage an iron rod half an inch in diameter and a foot long; no other means of producing electrical currents can compare with these machines in power. In Siemens' machine a series of compound horse-shoe magnets are arranged in a pile of considerable depth (fig. 26), each separated from its neighbour by a sensible space. The long narrow space between their poles encloses a powerful magnetic field. In this space a long coil of insulated wire is placed, wound round an iron core. In the fig. this coil and iron core are shown as though the end had been sawn off so as to show a section of the iron core and wires. The coil is wound lengthways from D to A, then across to B, then lengthways from B to C, and again across (where not shown) from C to D. The soft iron core with its coils are caused to revolve rapidly round a longitudinal axis. Currents are in consequence induced in the coil by an action identical with that described in § 50. The induced current is led off through two sliding contacts at T and T_1, to be applied as may be desired. In the most powerful form of machine this current is partly applied to strengthen the magnetism of the horse-shoe magnets by passing through coils wound round their poles. This arrangement gives rise to an accumulative action, the idea of which occurred simultaneously to Wheatstone and Siemens.

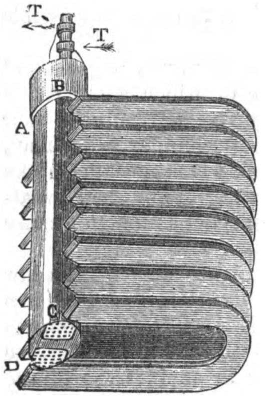

Fig. 26.

If a current due to some external source of energy be passed through the coils of a magneto-electric machine,

this current produces forces which tend to drive the machine backwards; that is to say, in the opposite direction to that which would induce a current flowing in the direction employed. Most magneto machines can therefore be used as electromotors, or electro-magnetic engines—that is to say, as machines in which a current due to some external source, such as a Voltaic battery (§ 66), is employed to give motive power.

§ 56. *Notes on Experiments.*—In apparatus such as have been described in this chapter it is usual to use *copper* wire, inasmuch as copper has a low specific resistance, can be bought at a reasonable price, is non-magnetic, and has considerable strength. Brass wire may have ten or twelve times the resistance of an ordinary copper wire of the same length and section. Thus in the above experiments, we should with a given induced electromotive force in equal circuits obtain only $\frac{1}{10}$th or $\frac{1}{12}$th of the current if brass were used instead of copper.

Iron wire must be excluded from the apparatus because of the direct magnetic effects which it would produce; moreover, its specific resistance is about seven times that of copper. The insulated wire used in the apparatus is usually covered with silk, and may with advantage be varnished with shellac. It is to be remembered that when a "coil" is spoken of, this always means a coil of wire so wound that each turn is so insulated from its neighbour that conduction can only occur along the wire and not across from wire to wire. Cotton may be used instead of silk, but does not insulate so well. Gutta-percha or india-rubber insulate wires excellently, but take up much more room than silk. In apparatus producing great electromotive forces much difficulty is often experienced in insulating adjacent wires in a coil; sparks will in these cases pass across silk or cotton. Care must be taken, when several conductors are joined to make a circuit, that the surfaces in contact are clean; a thin film of dirt or oxide will sometimes act almost as a perfect insulator, wholly stopping

the flow of a current when moderate electromotive forces are used.

§ 57. *Connection between the Law of Conservation of Energy and Electro-magnetic Induction.*—The currents obtained from magneto-electric machines are obviously the result of mechanical work. We expend work at a certain rate, usually described in terms of the horse-power employed in driving the machine; the useful effect of the horse-power thus expended is represented by a certain quantity of electricity driven through conductors under the action of electromotive force. The work which the current represents is (§ 41) proportional to the product $i\,q$; where q is the whole quantity of electricity moved under the electromotive force i in the time t; then the rate of useful work per unit of time is $\frac{i\,q}{t}$ or $i\,c$. If the efficiency of the electro-magnetic engine is constant under different circumstances we shall therefore find the product $i\,c$ directly proportional to the horse-power expended in driving the machine. The useless work done in driving the machine is represented by heat, which appears at the bearings, in the conducting wires (§ 72) and in the magnets themselves.

The law stated in § 49, that the E.M.F. induced in any element of a conductor moving across a magnetic field is proportional to the number of lines of magnetic force cut across in a given time, can be deduced as follows from the law of conservation of energy. This law requires that all energy expended by one part of a system shall be found in some form at another part of the system. Now, energy may be expended in two ways, namely, against a reciprocating or against a non-reciprocating resistance. Energy employed to compress a gas or a spring, or to lift a weight, or to separate two magnets, does work against a reciprocating resistance; the forces due to elasticity, gravitation, or magnetic attraction will give back work done against the action of these forces; this work may remain stored for any length of

time in the system after the work has been done. Energy expended in overcoming friction does work against a non-reciprocating resistance, as the friction will not in turn do work. Heat is in this case produced, and a definite quantity of heat is known to represent a definite amount of work or energy. Now energy is required to move a conductor conveying a current across a magnetic field in the opposite direction to that in which the field tends to move it; this energy does work against a non-reciprocating resistance and cannot be stored up in the field or in the current. The current indeed has no permanent existence; the current at each successive instant is a new current; the work done in moving the conductor must therefore be done on the current itself at the very instant of its motion, but there is no way of doing work on currents except by an E.M.F. This reasoning shows that an E.M.F. must act on any current moved across a magnetic field, and that this E.M.F. will tend to increase the current if the motion be in the direction opposite to that in which the mechanical force due to the magnetic field would move the conductor.

Moreover the work done by any E.M.F. called i on any element of a current c during a given time is proportional to $i\,c$; now the mechanical work done in moving the element across the field is proportional to the intensity of the field, the strength of the current, and the distance moved, if that component of motion be alone taken into account which is perpendicular to the lines of force; in other words, it is proportional to $n\,c$ where n represents the number of lines of force cut. But since $i\,c$ and $n\,c$ are both proportional to the same number, *i.e.*, to the work done, we have i proportional to n, Q.E.D.

§ 58. *Universality of Induction.*—There is no place in the neighbourhood of the earth which is not a magnetic field of greater or less intensity, and no conductor can move across a magnetic field without being traversed by induced currents; thus almost every motion

of almost all bodies on the earth produces currents traversing those bodies with all the complicated effects due to those currents. Our bodies are sensible of the beginning and ending of induced currents when these are of great magnitude, such as those produced by a Ruhmkoff's coil. If we were sensible of the indefinitely smaller currents induced in our bodies as we move, these would give us a sense of direction relatively to the lines of magnetic force. Graham Bell's telephone renders us indirectly sensible of currents which in magnitude are comparable with those continually produced by the motion of every conductor around us.

§ 59. *Graham Bell's Telephone.*—This instrument, used in telegraphy, is represented in fig. 27. M is a steel magnet, and D a thin soft iron disc, held at its edges by the case L, which serves to support the magnet. B is a coil of silk-covered wire, the two ends of which are taken to the terminals C C_1; E is a mouthpiece or ear-piece of wood, which leaves only a small part of the disc D exposed. Two instruments are connected, so that the two coils D may form part of one circuit. Usually a long insulated iron wire joins two terminals of the two instruments, and wires are taken from the other terminals to the earth, which thus forms part of the circuit. The part E of one instrument, which shall be called the receiver, is held to the ear. The person wishing to send a message speaks into the mouthpiece of the other instrument, which will be called the sender. The spoken words cause the air to vibrate in front of the sender, and the disc D of that instrument vibrates as the air does, alternately approaching and leaving the end of the magnet M. Each change in the position of the disc D causes a change in its magnetism and in the magnetic field occupied by the coil B. Each change in the magnetic field causes an induced current in the circuit. This current is reversed at each change of direction in the motion of the disc, and, moreover, its magnitude is at each instant sensibly proportional to the rate at which the disc D is moving; for we know that

the induced current is proportional to the rate of change in the field enclosed by the coil B, and we see that this rate of change will depend on the rate at which the disc D is moving. The induced currents acting on the receiving instrument will change the magnetism of the steel magnet M and the magnetic field in which the disc D of the receiver lies; each change will be accompanied by a change in the attraction of the iron disc to the magnet, and thus the disc D will be set in vibration. It will move to and fro as often as the direction of the current in the circuit is reversed; but more than this, its rate of motion at each instant will be proportional to the

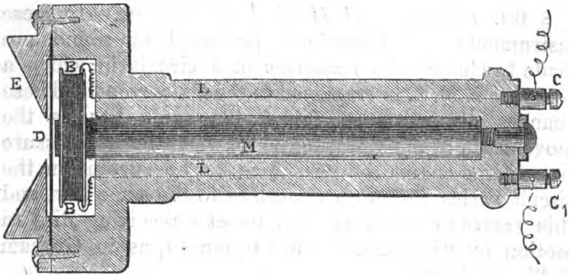

Fig. 27.

rate of change in the magnetic field it occupies. Now this rate of change is the same rate as that of the change in the current, which again is the same rate as that of the motion of the sending disc D. The motions of the sending and receiving discs will therefore be similar, though of unequal magnitude. The air therefore in front of them—which in one case moves the disc, and in the other is moved by it—will also vibrate in the same way; and since the vibrations of the air at the sending end produced the impression of articulate words on the ear, so the vibrations of the air caused by the disc D at the receiving end will also produce the impression of the same articulate sounds. The chief difference between the two sounds is one of

magnitude. There are several secondary actions which cannot be described in a short notice. Some of these tend to assist the main action, and others to impede or modify it. The action of the two discs is similar to that in the toy telegraph, where two parchment discs are mechanically connected by a tight string. The electrical currents due to induction give those impulses in the one case which in the other are given mechanically by the string. The currents circulating in the telephone are perhaps a thousand million times less than those which would cause an ordinary electro-magnet to attract a piece of soft iron close to its pole with a force equal to a few grains.

§ 60. *Edison's and Hughes' Microphone.*—In these instruments the vibrations produced by sound are made to change the *resistance* of a circuit in which a constant E.M.F. is employed to send a current. These changes of resistance follow the same law as the movements of the vibrating body, which by its pressure causes the change of resistance. The current in the circuit varies therefore according to the same law, and this varying current is used to set a receiving disc in motion by which sounds are produced, as in Graham Bell's receiver.*

CHAPTER V.

ELECTRO-CHEMISTRY.

§ 61. *Electrolysis.*—Fig. 28 shows a circuit, one part of which, D, is a liquid. Let A and C represent two sticks of graphite, B a metal wire of any length, and D molten bromide of silver in a capsule. Let an E.M.F. be produced in this circuit driving a current round the circuit in the direction of the arrow. When the E.M.F. between A and C exceeds a certain definite

* Graham Bell's Photophone acts in a similar way, the resistance of the circuit being made to vary by the incidence of light on selenium (§ 42).

amount the liquid will be decomposed. Bromine will appear at the stick A, and silver at the stick C. Numbers of compound liquids can by the action of an electric current be thus decomposed into their chemical constituents, and this action has received the name of *electrolysis*. The liquid D is called an electrolyte; an electrolyte may be a substance naturally liquid at ordinary temperatures, or a molten substance, or a substance in solution. Any solid conductor, A, from which the current enters the electrolyte is called an *anode*, or a *positive electrode*. Any solid conductor, C, into which the current flows from the electrolyte is called a *cathode*, or a *negative electrode*. The simple or compound constituents of D, which appear at the electrodes as the result of electrolysis, are called *ions*. The ion which appears at the anode is called an anion; the ion which appears at the cathode a cation. The ions are set free only at the surface of the electrodes. We may conceive this effect as due to a series of decompositions and recombinations along a chain of molecules joining the two electrodes. Thus while a cation particle appears at the cathode, the anion particle set free combines with the cation particle of the second molecule; the anion of the second molecule combines with the cation of the third molecule, and so on until the molecule is reached which touches the anode where the anion of the *n*th molecule finds no cation to combine with, and is consequently set free. These actions occur simultaneously. No trace of a free ion will be detected along the chain of molecules, provided of course the ions set free at the electrodes are prevented from afterwards mixing with the electrolyte. When set free the ions may adhere to the electrodes or combine with them; they may be diffused through the liquid, or may combine

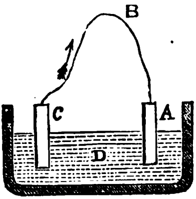

Fig. 28.

with some of its constituents; if in a gaseous form, they may escape into the air. Graphite is chosen for the electrodes in the above example, because the ions do not combine with this substance. We will call electrodes, which do not combine chemically with the ions, neutral electrodes. Chemical reactions due to the ions are called *secondary* actions.

The following rules as to the constituents into which compounds break up usually hold good, but they sometimes fail to indicate the ultimate result in consequence of secondary actions.

a. In binary compounds of metals, the metal is the cation.

b. Salts of the type of zinc or copper sulphate formed by the less inflammable metals can be electrolysed from their solutions in water, giving the metal as a cation while free acid with oxygen appear at the anode. An unstable compound of anhydrous acid with oxygen is here considered as the true anion. The water itself is not in these cases electrolysed.

c. Salts of the type of sodium sulphate formed of the more inflammable metals and electrolysed from a solution of water give alcali with hydrogen at the cathode, and free acid with oxygen at the anode.

In reference to case *a*, when the binary compound is soluble in water the primary result of the electrolysis from a solution is often masked by a secondary action. Thus in the case of sodium chloride (common salt) the primary action brings sodium to the cathode and chlorine to the anode, but the sodium when freed instantly combines with oxygen taken from the water, leaving, as the ultimate results, free hydrogen and soda at one electrode and chlorine at the other. There will be a further secondary action between the chlorine and water.

Ordinary water under the action of electrolysis behaves like a binary metallic compound, giving hydrogen at the cathode and oxygen at the anode. The decomposition of water proceeds much more freely when a little

acid is present in the solution, and the primary electrolysis is then conceived as acting on the acid (*vide* § 65).

In case *c* the result is due to a secondary chemical reaction.

Electrolytic action may be employed to plate objects. Thus any object used as a cathode in a solution of copper sulphate will be plated with copper. If in this instance the anode be made of copper the free acid and oxygen of the anion will combine with copper from the anode and re-form copper sulphate exactly equal in quantity to that decomposed by electrolysis. The solution will be maintained at a constant degree of saturation, and the effect may be described as a transference of copper from the anode to the cathode.

§ 62. *Laws.*—1. The weight of a given ion decomposed by a current is proportional to the strength of the current and the time of its action. 2. The weights of different ions decomposed by equal currents in the same time are proportional to the chemical equivalents of the ions. Thus the chemical equivalents of copper, silver, and oxygen being 31·75, 108, and 8, the current which in one minute will deposit one grain of copper, will in the same time deposit nearly three and a half grains of silver, or, if used to decompose water, will liberate a quarter of a grain of oxygen. The weight of each ion decomposed in a second by a certain current chosen as unity is called the *electro-chemical equivalent* of that ion and will be denoted by the symbol ϵ. 3. The following list is so arranged that each material named is a cation relatively to that which precedes it; that is to say, if the result of any electrolysis be two of these simple substances, that substance which appears earliest in the list will be set free at the anion.

Anion—	Oxygen	Chromium	Silver	Manganese
	Sulphur	Boron	Copper	Aluminium
	Nitrogen	Carbon	Bismuth	Magnesium
	Fluorine	Antimony	Tin	Calcium
	Chlorine	Silica	Lead	Barium
	Bromine	Hydrogen	Cobalt	Tellium
	Iodine	Gold	Nickel	Sodium
	Phosphorus	Platinum	Iron	Potassium
	Arsenicum	Mercury	Zinc	

4. Work is done in decomposing electrolytes and this work is for any one electrolyte proportional to the weight decomposed. 5. The chemical action at each cross section of the electrolyte, or of any number of successive electrolytes, is constant when the current is constant. The effect appears only at the surfaces of the electrodes, but the chemical action takes place continuously along the electrolyte in the form of successive decompositions and recompositions of each molecule. 6. For each electrolyte a certain minimum E.M.F. between the electrodes must be exceeded, or *complete* continuous electrolysis will not occur (*vide* § 65). The work done by a given current in decomposing various electrolytes is proportional to this minimum E.M.F. 7. Ohm's law holds good for currents passing through electrolytes, whether with or without electrolysis, but it seems probable that what we call the *resistance* in electrolytes is due to different molecular causes from those causing resistance in solid conductors.

§ 63. *Polarisation is a Reversal of Electrolysis.*—Electrolysis is reversible in certain cases; that is to say, if the E.M.F. producing electrolysis in a circuit with neutral electrodes be stopped, but the circuit be otherwise unaltered, the electrodes, ions, and electrolyte will produce an E.M.F. and consequent current in a reverse direction, accompanied by the recombination of the ions to form the electrolyte; thus in the example given at the beginning of the paragraph 61, bromide of silver will be formed and a current produced in the opposite direction to that shown by the arrow (fig. 28); again, if water be decomposed between neutral electrodes, such as platinum plates, and the E.M.F. producing the electrolysing current be then taken away, a current will flow in the opposite direction, *i.e.*, from the cathode to the anode through the electrolyte. *Polarisation* is the name given to the cause of this reverse or secondary current, and the polarisation is said to have been caused by the primary or electrolysing current. The word correctly

describes the condition of the electrolyte with free ions at its ends, these ions having an affinity for one another, and being held apart by a condition of the fluid which in the most general sense of the word may be described as one of polarisation (§ 32).

A source of energy is required to produce a current. Polarisation constitutes a source of energy in virtue of the chemical affinity of the ions. In separating these work is done, and this work is given back by the reverse action when the ions recombine. The E.M.F. due to polarisation is a maximum at the instant at which the electrolysing E.M.F. ceases; it falls gradually from this maximum to zero.

For each electrolyte there is a limit to the value of the E.M.F. which can be produced by polarisation. This maximum E.M.F. is produced whenever the electrolyte is completely electrolysed, and is equal and opposite to the minimum E.M.F. capable of producing complete electrolysis (law 6, § 62). If the primary or polarising E.M.F. is less than the maximum, the secondary E.M.F., or that produced by polarisation, is at the first instant equal and opposite to the primary E.M.F.,* and gradually diminishes to zero. An electrolyte with large polarised surfaces at the electrodes constitutes a large store of energy, as compared with the same electrolyte polarised to the same extent between electrodes of small surface. A sensible time is required to bring any electrolyte to the maximum condition of polarisation which a given E.M.F. can produce. When the circuit is broken the recombination of ions, or depolarisation of the electrolyte, occupies a very much longer time than when it is closed.

If a current be employed, as in § 61, to transfer copper from one electrode to another through a solution of sulphate of copper, when this current ceases we find no reverse action or polarisation. The positive E.M.F.

* Vide experiments on polarisation by Dr. Exner. Proceedings of the Vienna Royal Acad. d. Wissensch, 1878. The author wholly disagrees with Dr. Exner's views as to the contact theory of the Voltaic cell.

which would result from the decomposition of the sulphate of copper is exactly balanced by the equal and opposite electromotive force (§ 64) which would result from the formation of sulphate of copper at the other electrode. The electrolyte is in no sense polarised; the two surfaces in contact with the electrodes are similar to one another.

§ 64. *Chemical Affinity the Cause of Currents. Voltaic Cell.*—Chemical reactions occurring between substances forming a chain of conductors in a circuit always give rise to electromotive forces in that circuit. The reverse action after electrolysis (§ 63) is one instance of this law. The E.M.F. due to a given reaction will be positive, *i.e.*, it will tend to produce a current, if this reaction is due to chemical affinity; the E.M.F. will be negative, *i.e.*, it will tend to oppose the current, if the reaction is effected by the current in opposition to chemical affinity, in other words, if the substance is electrolysed. The reactions in question may occur between ions which have been electrolysed as in the examples in § 64. They may occur between an electrodo and some constituent of the electrolyte; or they may occur between constituents of successive electrolytes. The E.M.F. given by the combination of the constituents of a given compound is constant and equal to that required for its complete electrolysis.

The *Voltaic cell*, so called from its discoverer Volta, consists essentially of two electrodes joined by one or more electrolytes so chosen that the chemical affinities between the substances causes one of the electrodes to combine with some constituent or constituents of the electrolyte. The simplest Voltaic cell consists of two metals such as zinc and copper joined by an electrolyte such as acidulated water. A Voltaic cell produces a permanent E.M.F. in the circuit formed when the two electrodes are joined by a solid conductor as shown in fig. 28, and may therefore be employed to produce a permanent current. The E.M.F. produced by a Voltaic cell in the circuit is equal to the algebraic sum of the electro-

motive forces due to the separate reactions, each taken with its proper sign as it promotes or resists the ultimate action. The Voltaic cell produces a constant E.M.F. in the circuit so long as the chemical reactions which occur are constant in kind. It is difficult to secure this condition in cells consisting of materials so chosen that free gaseous ions appear at either electrode.

The reactions proceed with much greater regularity and intensity in Voltaic cells when the circuit is closed and the current flowing. The chemical affinity between the constituents of the compounds formed is the source of the energy employed in producing this current. When no current flows no energy, and consequently no chemical combination, is required. In most, if not all, cells some chemical action occurs even when the circuit is broken; this action, which involves waste, is accompanied by currents passing round irregular and uncertain circuits in the electrolyte.

§ 65. *The Daniell Cell.*—The form of Voltaic cell which is called, after its inventor, the Daniell cell has one electrode made of zinc and the other of copper; the zinc plate is plunged in a solution of sulphate of zinc; the copper plate in a solution of sulphate of copper. The two solutions must be in contact with one another, but must in some way be prevented from mixing mechanically. In the form shown (fig. 29) this is effected by the porous partition B.

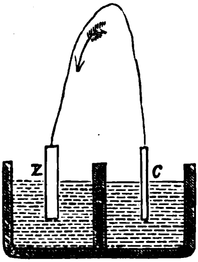

Fig. 29.

There are many forms of Daniell cell, which essentially consists of the series: zinc, zinc sulphate solution, copper sulphate solution, copper. When the circuit is completed, as shown in fig. 30, by a solid conductor joining those parts of the zinc and copper plates which are not covered by the solution, a

permanent current flows from copper to zinc through the wire and from zinc to copper through the solutions.

This current is accompanied by a series of reactions the reverse of those which would be caused by an electrolysing current forced against the E.M.F. of the cell, *i.e.*, driven from copper to zinc through the fluids. The electrolysing current would have the following effects:—

1. It would decompose the sulphate of zinc, depositing the metal on the cathode Z, and sending free acid and oxygen towards the anode C. 2. It would decompose the sulphate of copper, sending the free acid and oxygen to the anode C, and the copper towards the cathode Z. 3. The copper due to the second reaction, and the free acid and oxygen due to the first, would combine. 4. The free acid and oxygen at the anode would combine with the copper.

The ultimate effect would therefore be a substitution of copper sulphate for zinc sulphate in the electrolyte, accompanied by an increase in the quantity of zinc on the zinc plate and a decrease in the quantity of copper on the copper plate. When, therefore, the Daniell cell is allowed to produce a current in the opposite direction the ultimate effect is the reverse of this, viz., to substitute zinc sulphate for copper sulphate, to consume zinc and to deposit copper on the copper plate.

The electromotive force which a Daniell cell produces in a circuit is frequently employed as a practical unit of E.M.F. Measured in this unit the E.M.F. required to electrolyse zinc sulphate from a solution is expressed by the number 2·15 (§ 68). The E.M.F. required to electrolyse copper sulphate is 1·15; chemical affinity tends to produce the zinc sulphate and to oppose the decomposition of the copper sulphate. The E.M.F. of a Daniell cell is therefore (§ 64) equal to the *numerical difference* between 2·15 and 1·15. This unit of E.M.F. will be employed hereafter.

The word polarisation is not usually employed as describing the condition of the fluids between the elec-

trodes of a Daniell cell. Nevertheless we see that, as in the cases of polarisation described in § 63, the electrodes of a Daniell cell are in contact with the substances which would be brought to them by electrolysis due to an E.M.F. opposing the resultant chemical affinities of the cell. If in this case we conceive the materials to be polarised by an electrolysing current, we may equally conceive the same series of materials, when arranged in the same order, to be polarised by their chemical affinities, even though no electrolysing current has been employed to bring them to their respective places.

The name of poles is commonly given to the terminals by which external conductors such as wires are connected with the two electrodes of a Voltaic cell. In the present work the name of poles will be applied only to terminals which are of *one metal*. This metal may be the same as that of one of the electrodes. The E.M.F. between the poles of a Daniell cell when the circuit is not completed is the same as that which the cell will produce in the completed circuit (*vide* § 69). The pole by which the current leaves any cell is called positive; the other negative. Thus in a Daniell cell the terminal attached to the copper plate is the positive pole; the terminal attached to the zinc plate the negative pole.

§ 66. *Electrolysis of Water. Incomplete Electrolysis.*—In § 62 it was stated that a certain minimum E.M.F. between the electrodes is required to produce electrolysis. In the case of water this E.M.F. measured in terms of a Daniell cell is 1·42. Some current will pass through water or any other electrolyte between two electrodes if any E.M.F. whatever is maintained between these, no matter how small this E.M.F. may be.

The behaviour of the electrolyte when conveying small currents due to feeble E.M.F. between the electrodes is not fully understood. The work done by a current must in all cases be proportional to the product $i\,c$ (§ 57). The quantity of the electrolyte electro-

lysed is proportional to the work done, and by the law of electro-chemical equivalents is proportional to *c*; therefore, *i*, the E.M.F. effecting the decomposition must be constant. If, then, a current passes with a less E.M.F. than this constant value, we are led to suppose that *complete* electrolysis does not occur. Helmholtz, indeed, pointed out that complete electrolysis of water really did occur in all cases but that where the current was produced by an E.M.F. smaller than that which was of itself able to produce the decomposition, the action was due to free oxygen present in the water, which by its affinity for the combined hydrogen might reduce the work to be done by the passing current almost to zero. It is certain that dissolved gases in electrolytes do exercise considerable influence on their behaviour, and it is probable that when they are present some action similar to that suggested by Helmholtz takes place. When, however, no free oxygen can be detected in water a current will nevertheless flow if any, even the smallest, E.M.F. be maintained between the electrodes. It is then apparently impossible that the water should be *completely* electrolysed. No visible gases are given off. We are thus led to the conception that under the action of an E.M.F. smaller than 1·43 water is not *completely* electrolysed but merely polarised.

This hypothesis is consistent with the fact that the reverse E.M.F. due to the polarisation of water is at first exactly equal to the electrolysing E.M.F., when the latter does not exceed 1·43. The action of the electrolysing E.M.F. appears analogous to that of putting a stress or tension on a chain of particles in the water; if that stress is greater than is produced by an E.M.F. equal to 1·43 the material gives way and complete electrolysis is produced. If the stress is less than is produced by an E.M.F. equal to 1·43 the particles are not completely separated, and when the polarising force is removed, give back, as by elasticity, the work which was done to them. During the strained condition of water between electrodes when

incomplete electrolysis occurs, the substances present at the electrodes must be considered neither as hydrogen nor as oxygen, but as at one electrode a substance intermediate between hydrogen and water, at the other electrode a substance intermediate between water and oxygen. The number 1·43 is the value of the E.M.F. required completely to separate oxygen and hydrogen from acidulated water by means of large platium electrodes. If pure distilled water free from gas is used small platinum points used as electrodes can be polarised so as to give back an E.M.F. of about 2. This result is remarkable as apparently indicating that the substances then present at the electrodes have a greater affinity for one another than exists between simple oxygen and hydrogen. The number 1·43 experimentally obtained corresponds with that calculated by the means indicated in § 67.

The behaviour of water when holding salts in solution is remarkable; under the action of a sufficient E.M.F. zinc sulphate in solution is electrolysed while the water is not, although zinc sulphate requires a greater E.M.F. to separate its parts than water. The electrolysis of water containing an acid, for instance sulphuric acid, is believed to result from a secondary action as follows:—The sulphuric acid ($S O_3$, H_2O) is decomposed into hydrogen H_2, which goes to the cathode, and a substance $S O_4$, which goes to the anode; this substance unites there with H_2 taken from the water by a secondary action forming sulphuric acid, $S O_3 H_2O$, again, and leaving the oxygen of the water, O, free.

Let the oxygen and hydrogen obtained by electrolysis be collected in the test tubes O and H (fig. 30), round platinum electrodes partly exposed to the gas and partly covered by the slightly acidulated water which is being electrolysed. When the E.M.F. effecting electrolysis is stopped, a current, due in the first instance to polarisation, flows in the direction of the arrow; this current continues until all the oxygen and hydrogen have recombined. The action is arrested if the circuit is

broken. The E.M.F., at first equal to that required for complete decomposition, soon falls, probably because that part of the action, by which the gases leave the plate and fluid to collect in the test tube, is not reversible. When used to produce a current the arrangement is called a Grove's gas cell.

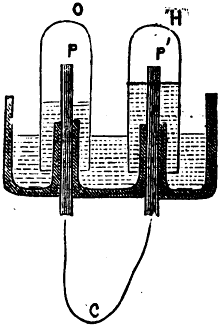

Fig. 30.

The apparatus shown in fig. 30 may be used to measure the current producing electrolysis in the acidulated water; this current will be proportional to the rate at which the gases accumulate (§ 62, law 1). The apparatus is then called a Voltameter, and with proper precautions gives approximately accurate results.

§ 67. *Single Fluid Cells. Smee's Cell.*—Volta employed a very simple cell, consisting of zinc and copper joined by flannel, moistened with slightly acidulated water. Zinc and platinum, or platinized silver, plunged as electrodes in a vessel of acidulated water form a simple and common Voltaic cell known as a Smee cell. Cells in which, as in this case, a single electrolyte is employed are called simple or single-fluid cells. Those in which, as in the Daniell, two fluids are employed are called double-fluid cells. If it were possible to maintain the electrolyte in a constant condition all Voltaic cells would give a constant E.M.F. In the Daniell cell this is practically possible. With a zinc and copper or zinc and platinum cell it is practically impossible, for when the current begins to flow the chemical action which consists in the combination of zinc with oxygen and acid sets free hydrogen, which, under the ordinary electrolytic action resulting from a current however produced, goes to the cathode or copper; its presence, whether fully liberated or partly liberated, causes a state of things which is different from that existing when the solution first

touched the copper. A reverse electromotive force is set up, which may be described as due to the affinity of the liberated or partly liberated hydrogen for the oxygen in the solution. This reverse E.M.F. is to some extent influenced by the metal with which it is in contact, inasmuch as from some metals the hydrogen escapes more freely than from others. The gradual accumulation of partly liberated hydrogen gradually diminishes the E.M.F. of the cell until, in the Smee cell, it falls to an amount equal to the difference between the E.M.F. required to electrolyse zinc sulphate and that required to separate hydrogen from oxygen, or ·73 in the unit employed above. The E.M.F. of the cell when in this condition may be raised considerably by brushing away the partly liberated hydrogen. Even the natural and intermittent escape of bubbles of liberated hydrogen affects the E.M.F. Any interruption in the current causes a considerable change in the state of polarisation of the fluid, and, therefore, in the current which flows when the circuit is first re-established. The E.M.F., of a Smee, sinks still lower when zinc sulphate is present in any quantity in the electrolyte. Those double-fluid cells which owing to secondary actions do not deposit gas on the poles are therefore preferred in practice. Cells of the Daniell type are very common. For many purposes they are more convenient as sources of a current than the magneto-electric engine. The chief expense their use entails results from the consumption of zinc, which is the metal usually employed at the negative pole.

§ 68. *Chemical Theory of the E.M.F. of a Cell.*—The total energy which can be exerted by the combination of a given weight of two chemical constituents in a Voltaic cell is equal to the work required to electrolyse the same weight of those constituents. This work can be measured in two ways: 1st. Let i be the electromotive force required to separate the two ions in question. This we know to be definite. Then, by § 41, the work done in forcing a quantity of electricity q

against this E.M.F. is proportional to $i\,q$; this expression, therefore, may be used as a measure of the work done by the quantity q of electricity in decomposing the given pair of ions. 2nd. The energy produced by the combination of any two ions is wholly employed in the production of heat when this combination takes place, not in the Voltaic cell, but directly without producing any electricity. Let θ be the heat so evolved by the unit weight of one of the ions, the electro-chemical equivalent (§ 62) of which is ϵ; the weight of that ion decomposed by the passage of the electricity q will be (§ 62) equal to $q\,\epsilon$, and the heat which this quantity would evolve by its simple combination will be $q\,\epsilon\,\theta$. Hence we have $q\,\epsilon\,\theta$ proportional to $q\,i$, since both expressions are proportional to the energy evolved by the combination, or, what is the same thing, required for the decomposition of the same quantity of the ion; hence i, the E.M.F. which this combination can produce, is proportional to $\theta\,\epsilon$, the heat evolved by the combination of the electro-chemical equivalent of that ion in the given reaction. The number $\theta\,\epsilon$ can be determined experimentally. This law was first stated and proved by Sir William Thomson, and illustrated by the experiments of J. P. Joule. The resultant E.M.F. of a complete cell in which several reactions occur is the sum of all the electromotive forces which each reaction can produce separately, counting those positive which tend to assist the resultant current, and those negative which oppose it. Those reactions produce a positive E.M.F. which occur in consequence of the chemical affinity of the ions; and those reactions produce a negative E.M.F. which occur in consequence of the electrolysis produced by the resultant current. If we were to polarise a Smee cell by some extraneous E.M.F. which coated the zinc with hydrogen, and the platinum with oxygen, we should, on removing the extraneous E.M.F., have at first only positive reactions. If we represent $\theta\,\epsilon$, the heat resulting from the oxidation of one electro-

chemical equivalent of zinc, by the number 41300, the value of $\theta\epsilon$, for the reaction by which the oxide produced combines with the acid to form the sulphate and then dissolves, will be represented by the number 11077. The E.M.F. of the cell which the cell in this condition could produce will then be measured in a certain unit by the sum of these two numbers, or 52377. In a Daniell cell the same reactions occur, but there are in addition two reactions, giving rise to a negative E.M.F.: firstly, the formation of the oxide of copper; and, secondly, its combination with acid to form a salt and dissolve. The values of $\theta\epsilon$ for these two reactions are 18876 and 9200—hence the E.M.F. of a Daniell cell in the same units as those just employed for the Smee is $52377 - 28076 = 24301$.

The two numbers 24301 and 52377 obtained by experiments on the heat of combination and the two numbers 1 and 2·15 obtained by the direct comparison of the E.M.F. of a Daniell cell and the electrolysis of sulphate of zinc are very closely proportional to one another. When the oxygen which we have supposed to be collected in the Smee cell is consumed we shall have a reaction tending to produce a negative E.M.F., namely, that required to electrolyse water. Expressed in the above thermal units the heat of combination of the electro-chemical equivalent of hydrogen and oxygen is 34741, hence the final E.M.F. of a Smee cell will sink in the thermal units to 52377—34741 or 17636, which corresponds in fractions of a Daniell cell to about 0·72, which represents accurately the result obtained from the direct comparison of a Daniell cell and a Smee which had attained its permanent condition. The inconstant E.M.F. of a Smee cell should from this reasoning lie between 2·15 Daniell and 0·72. The conclusion to be drawn from the close agreement between theory and observation is that the chemical reactions of which account is taken are really the actions operative in producing the current, and secondly that the energy

they develop is wholly employed in producing the current.

§ 69. *Contact Theory of E.M.F.*—We already know (§ 3) that any two substances in contact are at different potentials (§ 41) and so exert an E.M.F. The electromotive force due to contact between solids all at one temperature is subject to the following law: If A and B by their contact produce an E.M.F. equal to m, and if B and C by their contact produce an E.M.F. equal to n, then A and C by their contact produce an E.M.F. equal to $m+n$. From this law it follows that no circuit of solid conductors at one temperature can produce a current, for the resultant E.M.F. is necessarily zero. Thus, if in the above case we arrange three metals A, B, C in a ring, the E.M.F. due to the contact of A with B and B with C is exactly counterbalanced by the opposite E.M.F. where C touches A. A similar result follows whatever be the number and arrangement of solid conductors in a circuit; the sum of the electromotive forces due to their contact is necessarily zero.

When an electrolyte forms part of the circuit, and is placed, as in the Voltaic cell, between two conductors, for which it has different chemical affinities, the above law no longer holds. That is to say, if B be an electrolyte in a circuit composed of A, B, and C, we find that the E.M.F., or difference of potentials, between A and C (say zinc and copper) is not equal to the sum of m and n, the electromotive forces due to the contact of A with B and B with C. This fact may be considered as due to the polarised condition which the electrolyte assumes in consequence of the chemical action between it and the conductors (the word polarised is here used in its most general sense). Let l be the E.M.F. observed as due to the contact of A and C, then the E.M.F. of the complete circuit is equal to the sum $l+m+n$, each of which magnitudes may be positive or negative. This law enables us to calculate the E.M.F. of any circuit by merely adding the several values of the separate electromotive forces at each junction in the circuit;

giving each its proper sign. In making this calculation all junctions between any one solid conductor at a uniform temperature and other solid conductors on each side of it may be omitted; the effect of the junction at the one end cancels the effect of the junction at the other. Thus the E.M.F. acting to send a current round a solid circuit, including a Daniell cell, when first put in action may be calculated by adding the four electromotive forces due to copper and zinc, zinc and zinc sulphate, zinc sulphate and copper sulphate, copper sulphate and copper. This law, first enunciated by Volta, has often been considered as opposed to that enunciated in the last paragraph.

Both laws are true, which proves that the value of l, although not equal to $m+n$, differs from this sum by an amount depending on the difference of the chemical action of the electrolyte on A and B.

The electromotive force between the electrodes of a cell, as for instance between zinc and platinum in a Smee cell, is not the electromotive force which this cell produces in the circuit when the zinc and platinum are joined by a solid conductor. In the first case we have only two effective junctions, and in the last case three. If, however, we join a small piece of platinum to the zinc outside the cell, as in fig. 31, then the electromotive force between the poles P and P′ of the same metal (§ 65) is the whole electromotive force which the cell can produce in a circuit. This value is called the electromotive force of the cell, and is that which is calculated by the chemical theory (§ 67).

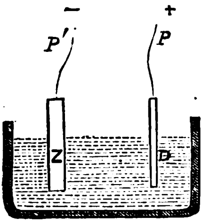

Fig. 31.

In all Voltaic cells practically in use, the metals plunged in the electrolyte are attached either to brass screws or copper wires called terminals, by which other conductors can be joined to the cells. These terminals are of one metal, and the electromotive

force or difference of potential between them is the full E.M.F. of the cell. It must be remembered that in this work, in speaking of the poles of a cell or battery, we refer to terminals of one metal.

The following numbers give, in terms of the E.M.F. of a Daniell cell taken as unity, the differences of potential produced by the contact of the substances occurring in that cell.* In each pair the substance first named takes the higher potential. Zinc – copper 0·649 ; copper – copper sulphate solution 0·061 ; zinc sulphate solution – copper sulphate solution 0·082 ; zinc sulphate solution – zinc 0·372. Hence in a Daniell cell of these materials, if a copper pole joined to the zinc electrode be at zero potential, the potentials of the other parts will be : zinc 0·649 ; zinc sulphate sol. 1·021, copper sulphate sol. 0·939 ; copper electrode and pole 1·0.

It is more difficult with single fluid cells to obtain measurements which are consistent with the electro-chemical theory, on account of the changes produced by changes in the degree of polarisation of the electrolyte ; this polarisation must, when regarded by the light of the contact theory, be considered as due to the fact that the substances in contact at the surface separating the electrolyte from the electrode are altered by the polarisation.

§ 70. *Voltaic Battery.*—When the positive pole of one Voltaic cell is joined to the negative pole of a second, the E.M.F. between the negative pole of the first and the positive pole of the second is equal to the sum of the electromotive forces of the two cells. By using n equal cells we can obtain n times the electromotive force of one. A series of cells joined in this way is called a Voltaic, or galvanic, *battery*. By the use of Voltaic batteries powerful and constant currents can be maintained. The magnitude of the current depends

* These numbers are reduced from those given in Messrs. Perry and Ayrton's paper on "The Contact Theory of Voltaic Action," No. III. Phil. Trans. Roy. Soc., p. 15, part I., 1880.

on Ohm's law (§ 42). In applying Ohm's law, it is necessary to remember that each cell has a resistance. This resistance is great in small cells, but can be diminished by increasing the size of the plates plunged in the electrolyte, and by bringing these closer together. The E.M.F. is not affected by the size of the cell, or of the plates plunged in it. If cells are joined, so that all the positive poles are in contact, and all the negative poles in contact, they are said to be joined in multiple arc. The effect of joining similar cells in multiple arc is simply to diminish the resistance across the electrolyte between poles. The E.M.F. of the combination is the E.M.F. of one cell.

§ 71. *Electrostatic effects of Cells and Voltaic Batteries.*—A Voltaic cell produces a difference of potential between its poles, and when the circuit is not completed this difference of potentials is equal to the E.M.F. of the cell. The poles of a cell or battery may be joined to insulated conductors of any size or form, which, if of one material, are thereby kept at potentials differing by an amount equal to the E.M.F. of the cell or battery. This is the most convenient plan of producing and maintaining a given difference of potential between any two points. If one pole of a cell or battery be joined to the earth, that pole is usually treated as being at zero potential, although really the metal must be at a potential differing from that of the earth by an amount depending on the nature of the substances in contact (§ 68); calling the potential of the uninsulated pole zero the potential of any insulated homogeneous conductor connected with the insulated pole, and of the same metal, will be equal to the E.M.F. of the cell. The electromotive forces of cells or batteries may therefore be compared by an electroscope or electrometer (§ 22). The cell or battery may be used to charge a condenser or Leyden jar (§ 23) by joining the poles to the coatings of the jar, one pole to each coating. Powerful effects, such as sparks and shocks, are obtained when batteries of numerous cells in series are thus used.

When a circuit including a constant cell or battery is closed the difference of potentials between the poles is somewhat less than the E.M.F. in the circuit. The diminution is small when the resistance external to the cell is large compared with its internal resistance. The diminution is due to the fact that the external resistance is not the whole resistance in the circuit.

The potential of any homogeneous conductor joining the poles is highest at the positive pole, and lowest at the negative pole; at intermediate points the potential has intermediate values which may be calculated by the following law:—Let two points in a homogeneous conductor be maintained at a difference of potentials equal to i; let the resistance of the conductor joining the points be r and let the resistance separating any point A from the point of highest potential be l; then the difference of potential between the point at highest potential and A will be $\frac{li}{r}$; when the two points are joined by a series of conductors each homogeneous in itself, the distribution of potential in each follows the above law, but at each change of material, as from copper to iron, a sudden change of potential occurs determined by the principles of § 68.

The earth very frequently makes part of a Voltaic circuit, as in telegraphy, where one pole of a battery is

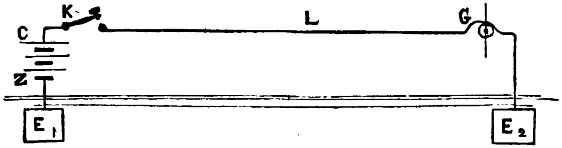

Fig. 32.

connected with the earth and the other pole to a long wire which is again connected with the earth at a distant station but elsewhere insulated (fig. 32). Whenever a current is sent along this wire its surface will receive a

statical charge, for by the principles just explained the passage of the current modifies the potential of every point in the wire, raising it if the current flows from the positive pole into the wire, or lowering it if the current flows from the negative pole into the wire. This electro-statical charge is chiefly important where the conductor conveying the current is near the neighbouring uninsulated bodies, as for instance in the case of submarine cables where the internal conductor is separated only by a thin coating of gutta-percha from the sea. The insulated conductor of these long cables forms a Leyden jar of large capacity, the dielectric being the gutta-percha (§ 23). Each time a current is sent through the conductor the cable is charged, each time the current ceases and the cable is joined to earth it is discharged. Similar effects occur in aërial lines, but the capacity is comparatively small.

CHAPTER VI.

THERMO-ELECTRICITY.

§ 72. *Heating Produced by a Current.*—A current in a solid simple homogeneous conductor heats that conductor; the heat produced in a conductor by a current c flowing for a time t from one point to another, between which points an E.M.F. equal to i acts, is proportional to the product $i\ c\ t$; this heat is, therefore (§ 41), proportional to the work done by the quantity q, equal to $c\ t$, passing between the points in question. Expressed in suitable units, based on the experiments of Joule, the heat and work are equal. The current which thus heats a conductor does no other work. An electrolyte is little if at all heated by a current passing through it. The work done by the current is wholly, or very closely, represented by the chemical action

produced. We do not know in what form a current does work when it passes through a solid compound body such as gutta-percha. Metal wires can be rendered incandescent or melted by the passage of a current. A thin short wire shows the effect more readily than a long thick one, because less work is required to heat it. Carbon can also be rendered incandescent. Some forms of electric lamps offer illustrations of these facts. Heat produced in this way may be called the Joule effect, from J. P. Joule, who first established the definite numerical relation between heat and work.

§ 73. *Heat Produced when the Circuit is not Homogeneous.*—When a current passes from one body to another the junction is, almost invariably, heated or cooled. This effect, called from its discoverer the Peltier effect, is independent of the Joule effect. If a current passing from metal A to metal B *heats* the junction, a current passing from B to A through the same junction at the same temperature *cools* the junction; the metals can be ranked in lists such that, at any given temperature, a current passing from one to any other subsequent in the list cools the junction, but passing in the opposite direction heats it. The rank of the metals in these lists varies when the temperature of the junction varies. Thus below 260° C. copper stands above iron; above 260° iron stands above copper. At 260° C. a current neither heats nor cools a copper-iron junction.

The passage of electricity between parts of a body at different temperatures tends to produce a rearrangement of the heat. In certain bodies, as copper, a positive current flowing between unequally-heated parts carries heat with it. In other bodies, as iron, when a current flows between unequally-heated parts, heat is carried against the direction of the positive current. This effect is called the Thomson effect, from its discoverer Sir William Thomson.

§ 74. *Thermo-electric Currents.*—In a circuit made of two materials, if one junction be kept hotter than the

other a current flows round the circuit. This current is due to a reversal of the Peltier and Thomson effects in the following sense:—When a current tends to produce heat at a junction, heat at that junction produces an E.M.F. in a direction opposite to that current; when a current tends to cause heat to flow in a given direction, heat flowing in that direction produces an E.M.F. in a direction opposite to that current. Thus a copper-iron junction below 260° produces an E.M.F. tending to send a current from copper to iron across the junction; above 260° the E.M.F. would be in the opposite direction. An unequally-heated copper rod produces an E.M.F. tending to send a current from the cold to the hot end; currents due to these thermal sources are called thermo-electric currents. The energy required for their production is due to heat which disappears at those parts of the circuit where electromotive forces act in the direction of the resulting current. The E.M.F. due to thermal causes in any circuit composed of a series of materials is the algebraic sum of the electromotive forces due to the reversal of the successive Thomson and Peltier effects—the word reversal having the sense above described. Thermo-electric batteries or piles are made by placing pairs of metals or alloys in a series such that each junction is alternately hot and cold. If n equal pairs be used the E.M.F. of the battery will be n times that of each pair. Bismuth and antimony are often used in this way; about 80 pairs with a difference of one degree centigrade at a mean temperature of about 20° C. will give an E.M.F. equal to $\frac{1}{100}$th of a Daniell cell. Piles of this kind are used to indicate small differences of temperature between the junctions by means of the currents produced; these currents are observed on galvanometers of small resistance. Certain alloys are considerably superior to bismuth and antimony for the construction of thermo-electric piles.

§ 75. *Sparks, Voltaic Arc.*—The electric spark is matter rendered incandescent during the passage of

electricity across a gas separating two conductors. A spark will set fire to any combustible gas across which it passes. A current passing as a brush across gas heats that gas—hot and rarefied gas resists the passage of a current less than cold and dense gas; the name Voltaic arc has been given to the brilliant incandescent junction formed by hot rarefied gas between two solid parts of an electric circuit. The Voltaic arc between two carbon terminals constitutes one form of electric lamp. Very beautiful thermal and optical phenomena accompany the passage of electricity through rarefied gases.

CHAPTER VII.

TELEGRAPHY.

§ 76. *Telegraphic Signals.*—Let a circuit be arranged as in fig. 32, where Z C indicates a Voltaic battery; E, a plate connecting the negative pole of the battery with the earth; K, a key, *i.e.*, a simple contrivance by which the positive pole C of the battery can at will be insulated or connected with the line L, which is a long insulated wire reaching from the sending to the receiving station. G indicates an instrument by which signals are perceived at the receiving station, where E_2 is an earth plate; L is connected with E_2 through wires forming part of G. If G be a galvanometer, the index will deflect when the circuit is completed by a person depressing the handle of K, and will return to zero when the circuit is broken. This fact allows intelligence to be sent from a person at K to a person at G by means of an alphabet, the constituent symbols of which may depend on the duration, extent, or direction of the deflexions of the galvanometer. The following table shows the "Morse" alphabet, depending on groups of long

and short symbols. Each symbol may be seen as by the deflexion of the needle of a galvanometer; heard as by the tap of an armature attached and released by the current passing through an electro-magnet at G; or recorded as a stroke on paper drawn past a marker attached to a similar armature; a line is drawn on the paper so long as the current passes :—

A · —	J · — — —	S · · ·
ä (æ) · — · —	K — · —	T —
B — · · ·	L · — · ·	U · · —
C — · — ·	M — —	ü (ue) · · — —
D — · ·	N — ·	V · · · —
E ·	ñ — — · — —	W · — —
é · · — · ·	O — — —	X — · · —
F · · — ·	ö (œ) — — — ·	Y — · — —
G — — ·	P · — — ·	Z — — · ·
H · · · ·	Q — — · —	Ch — — — —
I · ·	R · — ·	

G may consist of an electro-chemical arrangement by which the current while passing G effects the visible electrolysis of some salt. If paper moistened with a solution of such a salt be uniformly drawn under the end of a wire connected with L and over a plate connected with E_2 electrolysis will produce long and short visible marks when long and short currents are sent by K. This is Bain's chemical telegraph. With the aid of synchronous motions at K and G it is obvious that a pattern at K may be reproduced at G. In place of the key at K let a rotating handle be arranged over a disc round which the letters of the alphabet are printed, and fitted with contact pieces such that, each time the handle passes a letter, the circuit is completed and again broken. Let G represent a corresponding dial and pointer connected with clockwork such that each time a current passes the pointer moves forward one letter. Then as the handle at K rotates, the index at G, set at the outset to correspond with that at K, will follow step by step. If the operator at K pauses with his handle over a given letter, the index at G will pause opposite the same letter; words can be thus spelt out. Such instruments are called step by step instruments. With extra

mechanism they can be used to print instead of merely to show letters.

Returning to the simple galvanometer arrangement; the key K is easily modified so that the operator can by pressing one or another finger piece send at will positive or negative currents into the line. This gives another elementary symbol, and enables an alphabet to be formed of right and left deflexions instead of long and short indications. This arrangement forms the "single-needle" telegraph. When the galvanometer is a mirror instrument, such as that described in § 51, we have the arrangement introduced by Sir William Thomson for long submarine cables. The small inertia of the moving parts is of vital importance for signals, when, as is the case with these lines, the current takes a sensible time in reaching its maximum or permanent condition. Instead of using a battery, we may employ magneto-electric arrangements to produce the currents at the sending station. The force which the Voltaic circuit enables us to exert at a distance may be employed to ring bells, to control the movements of clocks, and for many other useful purposes. Indeed, the Voltaic circuit is already in some cases used to transmit power. A magneto-electric machine driven at one part of a circuit drives a similar machine at another part of the circuit.

Electricity cannot be said to have a velocity in the same sense as light has a velocity. The time of transmission of an electrical effect depends on very numerous circumstances in each case, but is always small. The first experimental application of electricity to telegraphic purposes was made by the late Sir Francis Ronalds, who in 1823 sent messages through an insulated wire 8 miles long from a source of electricity at one end to an electrometer at the other. Electric telegraphy was practically introduced by Messrs. Cooke and Wheatstone in 1837.

§ 77. *Telegraphic Lines.*—The insulated conductors used to connect two stations are either aërial lines, *i.e.*,

wires supported on insulators fixed at some height to poles, or submarine and subterranean lines, *i.e.*, copper wires covered with gutta-percha or india-rubber, and lying under the sea or earth. The iron aërial conductors have usually a greater resistance than the copper conductors of submarine lines, but they have a smaller capacity per mile because of their greater distance from surrounding uninsulated conductors. Aërial lines are fixed to insulators of porcelain, stoneware, or vulcanite, of various forms, all designed with the object of maintaining some part of the surface dry and clean, so as to insulate the wire from the earth in all weathers. Submarine and subterranean conductors are insulated by a continuous sheath of insulating material, selected, prepared, and applied with extraordinary care.

§ 78. *Tests for Faults.*—A single small imperfection, or fault as it is called, in the insulating sheath of a cable may develop in time so far as completely to stop communication through perhaps 2,000 miles of cable. It becomes, therefore, of extreme importance that experimental tests should be applied during manufacture, showing whether any such imperfection does exist, and again, if after a cable has been laid a fault occurs, to detect its position. All these tests depend on the numerical measurement of electrical quantities. Thus, if the copper conductor were to break inside the insulating sheath, we could ascertain the distance of the break by measuring the capacity of the conductor up to the interruption, and dividing the result by the capacity per mile. The quotient gives the distance of the fault in miles. If the cable break completely, so as to thoroughly expose the copper wire to the sea, we measure the resistance of the conductor which remains connected with the land, and dividing this number by the number expressing the resistance of the conductor per mile we obtain the distance of the break in miles. These two simple examples may serve to show the principles on which more complex cases are dealt with.

CHAPTER VIII.

CONCLUDING.

§ 79. *Currents in Nature.*—The Voltaic circuit as hitherto studied has consisted of a series of conductors so joined and placed that the current should flow simply *along* the circuit, or in other words at right angles to all sections made perpendicularly to a line showing the direction in which the conductor guides the current. We do not in nature meet with Voltaic circuits arranged in this simple manner. In nature we find no long insulated conductors in any way similar to telegraph wires. We do, however, find arrangements somewhat analogous to the Voltaic cell, wherever two different conductors are joined by an electrolyte which acts chemically on one or both; but these electrodes and electrolytes are not contained in insulating jars, nor have they poles joined by an insulated conductor. Nevertheless electromotive forces are in action all round us, and currents of greater or less magnitude are circulating through every conductor. Wherever solid conductors or parts of a conductor not perfectly homogeneous touch an electrolyte with which they have any chemical affinity, there we find not merely a difference of potential due to simple contact, but also a source of energy, partly at least, employed in maintaining a Voltaic current. In all such cases electricity will flow through the electrolyte and neighbouring conductors. The difference between these currents and those in insulated wires is analogous to the difference between currents of air in an open space and currents of air forced along an enclosed pipe. Similarly thermo-electric action gives rise to currents wherever conductors touch which are not perfectly homogeneous and at one uniform temperature, that is to say, practically in every natural solid and fluid. Again, the motion of every conductor in the earth's magnetic field gives rise to electromotive forces producing displacements of electricity,

that is to say, currents. The movement of statically electrified bodies, such as thunder-clouds, and indeed generally every displacement of air over the surface of the earth, produces a modification in the distribution of electricity in the neighbouring conductors, this change being effected by currents from place to place. Friction and certain vital processes must be added to the causes producing electric currents in nature.

Besides mere local currents due to local causes currents may be observed to flow through the earth for hundreds of miles mainly in one direction. The cause of these currents is not yet known with certainty. Some have supposed that the earth's magnetism is an effect of such currents circulating from east to west, and due more or less indirectly to the action of the sun. Sudden disturbances in the direction and intensity of these earth currents cause the so-called magnetic storms during which the condition of large parts of the earth's magnetic field varies rapidly.

§ 80. *Physiological Effects of Currents.*—The numerous, almost omnipresent currents in nature produce, so far as we know, very trifling effects on organised beings. Our senses take no cognisance of them, although it is conceivable that living beings might directly perceive the flow of electricity; indeed, a sufficiently powerful current can in one way be directly perceived, for when the tongue forms part of a circuit conveying such a current the observer experiences a peculiar sensation or taste, the absence or presence of which is often used as a test of the presence or absence of a current in the circuit. A very powerful current may flow through other parts of our body without being perceived in any way, but the commencement or cessation of such a current will be recognised by a peculiar twitch or shock. A rapid succession of short currents involving a numerous series of these twitches or shocks tends to deprive those parts of the body which the currents enter and leave of their power of voluntary motion. Use is made in medicine of this and other less well-

marked physiological effects due to currents directed through certain parts of the body. The effects of electrolysis are also used to produce certain modifications in unhealthy tissues; and the heat produced in a wire by a current has been made use of to produce the actual cautery. No medicinal application of electricity should be made except under the advice of a competent doctor. Certain animals, such as the gymnotus, possess organs by which electrical effects can be produced at will. The source of energy in these cases appears to be chemical, and the organ itself to be somewhat analogous to a Voltaic battery of many cells.

§ 81. *Concluding.*—We have been led to the knowledge that chemical action, heat, motion, friction, and other minor causes produce perpetual modification in the electrical condition of all matter; that the currents which accompany these modifications in their turn cause chemical, thermal, mechanical, and other minor actions. These actions and reactions baffle our imagination by their extent and complexity, but are nevertheless subject to simple definite laws, which laws enable us, whenever we can start from a numerical statement of the circumstances of a given electrical problem, to arrive at a numerical value for any effect, electrical, chemical, thermal, or mechanical, produced under those circumstances. Calculations such as these can be applied with great accuracy to electrical tests or laboratory experiments, because the conditions of each problem can in those cases be determined with nicety. When dealing with general electrical phenomena in nature we are usually unable to determine the conditions with precision, but we can in all cases state the conditions with at least so much accuracy as to fix some limits within which any given electrical effect must remain. The ignorant sometimes regard electricity as an agent of such unknown magnitude and nature as may afford at least a possible explanation of any and every phenomenon which they do not understand. No one can remain thus ignorant who has once grasped the

fact that the relations between electrical and other physical phenomena can be measured, that is to say, accurately and fully expressed by numbers.

The absence of special bodily senses by which the effects of electricity could be directly perceived (§ 31, 58) has probably much to do with a vague impression felt by the uninstructed that electrical phenomena are in some way more mysterious than the manifestations of heat, light, or gravitation. In truth, the laws of electricity are neither more complex nor less well known than those of any other branch of physical science. All physical effects are indissolubly connected. Even in this treatise, elementary as it is, we have been forced to consider the relations of electricity and magnetism to mechanical action, chemical affinity, heat, and light; these relations indicate that an essential unity underlies all the various forms or aspects of physical energy.

THE END.

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